SYMPATHECTOMY

AN

ANATOMICAL AND PHYSIOLOGICAL STUDY
WITH CLINICAL APPLICATIONS

enfermé dans une Gaine avec le Nerf de la 8me Paire, & on ne peut couper l'un sans l'autre, mais il est bien sûr que ce Nerf de la 8me Paire n'a aucun rapport aux Yeux, ainsi tout ce qui arrive aux Yeux par cette opération ne peut jamais être attribué qu'à l'Intercostal. Dans toutes les expériences de M. Petit les effets qu'on auroit cru devoir plus naturellement provenir de ce que l'Intercostal étoit coupé, la perte ou l'affoiblissement de la voix, les vomissements, les palpitations de cœur, &c. ont tous varié, & varié considérablement, & jusqu'au point de manquer quelquefois, mais ceux qui appartenoient aux Yeux ont été beaucoup plus constants, les Yeux sont devenus ternes, ils ont diminué, ils ont jetté de la Chassie ou des larmes, la Cornée s'est applatie, une membrane cartilagineuse qui coule sur le bord de la Cornée s'est étendüe, & en a couvert une partie, la Conjonctive s'est enflammée, &c. car nous supprimons un détail trop particulier. Et *afin qu'il ne reste aucun doute sur ces accidents* des Yeux, ils ne sont jamais arrivés qu'à l'Oeil droit ou au gauche, quand l'Intercostal n'a été coupé que de l'un ou de l'autre côté.

Il est donc bien démontré que l'Intercostal porte des Esprits dans les Yeux, mais comme ce n'est qu'en certaines parties des Yeux, le désordre que cause la section de ce Nerf arrive parce que quelques parties sont privées des Esprits qu'elles eussent dû recevoir, tandis que d'autres ne le sont pas. Toutes les parties du Corps animal sont en quelque sorte arc-boutées les unes contre les autres, & se tiennent en état par cet équilibre. Celles à qui il manque des Esprits qui leur appartenoient, perdent la tension nécessaire, se relâchent, & d'autres profitent aussi-tôt de leur foiblesse, & usurpent sur elles. Les liqueurs qui ne coulent plus assés facilement dans des vaisseaux relâchés, s'y amassent, & si la liqueur est du sang, voilà une inflammation; si c'est celle qui doit comme dans les Yeux entrer par les *Points lacrimaux*, & qui ne le peut plus, du moins en assés grande quantité, ce sont des larmes, ou de la Chassie, qui coulent au dehors. Il se peut

FIG. 1. Facsimile from *Histoire de l'Académie Royale des Sciences, Paris.* du Petit (1727).

[*Frontispiece*

SYMPATHECTOMY

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TO THE MEMORY OF

S. S.

A patient and a veterinary student upon
whose body many observations were made. She had always
shown much interest in this research
although at that time it was only in its early stages. After
leaving hospital after the operations and before
she had to return, as she realized, to die, she particularly
requested her relatives to grant permission
for a post-mortem examination if for research purposes
this should be asked for

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FOREWORD

PLANNED and deliberate operations for removal of parts of the sympathetic nervous system have been carried out for some eighty years. Many of the earlier surgical interventions were based on faulty ideas concerning the function and structure of the autonomic nervous system. In the last thirty years, however, our knowledge of this system has become much clarified. As a result the indications for sympathectomy have become much more rational, and tests, based on sound physiology, are currently available to assess the probability of a successful outcome of a surgical intervention in a particular patient. The action of drugs on the autonomic nervous system is also now much better understood, and important advances have been made in our knowledge of its detailed anatomy.

Nevertheless, and notwithstanding such clarification, there are still many problems posed by the system. Thus it is surprising that so little has been established concerning the more remote effects of sympathectomy. There is also much confusion in the literature on post-operative regeneration of autonomic fibres. Indeed some of the alleged rapid regenerations could only be described as miraculous if it were not apparent that they can, more rationally and quite satisfactorily, be explained by faulty operative technique or by the failure to recognize the existence of alternative pathways. Furthermore the follow-up of patients subjected to sympathectomy has often been casual; both in the living and after death interest has been directed almost exclusively to the clinical and pathological conditions rendering the sympathectomy necessary. Almost no attention has been given to the long range effects of such operations on the function and structure of the sympathetic nervous system itself. It is remarkable that effectively no autopsy reports are available on sympathectomized patients which enable a precise statement to be made on exactly what parts, and how much, of the sympathetic chain was removed or on what effect there had been on the structure of the remaining portions of the chain.

In this volume Dr Monro has brought together careful observations on a large series of patients who had been subjected to various types of sympathectomy. These patients were studied over extensive periods of time and the ultimate effects of the operations on the functional activity of the intact parts of the sympathetic nervous system have been most carefully assessed. The work reported covers a period of some ten years. Incorporated in the volume is material from Dr Monro's M.D.

thesis which was accepted by the University of Cambridge in 1954. This thesis was awarded the Raymond Horton-Smith Prize, as the best M.D. dissertation submitted that year. He has now brought the data on his patients up to date and provides what, in my opinion, is the best available account of the long range effects of sympathectomies on the autonomic nervous system of Man. Dr Monro's findings will, I believe, be of considerable interest to surgeons, clinicians, physiologists, pharmacologists and anatomists. I warmly recommend his volume to the attention of all who are concerned with problems involving the human autonomic nervous system.

J. D. Boyd

Cambridge
December 1958

PREFACE

This monograph is a report of ten years' work on problems affecting the sympathetic nervous system and the operations of sympathectomy. It has entailed continued observations on more than fifty individual patients for periods up to four years, and most of these patients continue to attend for re-examination. A few patients have died and this report includes detailed findings of a post-mortem examination on one patient who had previously been tested after paravertebral sympathectomy. This section provides detailed anatomical information on the lumbar intermediate sympathetic ganglia. The importance of these ganglia and the part they play in the retention of autonomic function after sympathectomy was first made clear in a paper published jointly with Professor J. D. Boyd in 1939.

The two principal methods of investigation of the clinical cases have been to record the patterns of sweating activity in order to detect the presence or absence of intact sudomotor pathways, and to measure blood flows in the fingers and toes in order to detect the presence or absence of vasomotor innervation. These methods are among the most sensitive for detecting sympathetic activity in man. No other report has considered the combination of these two techniques as a method of assessing sympathetic activity, nor has any report been made of the changes of either of these forms of activity which occur at varying, and at repeated, intervals after sympathectomy.

The monograph is divided into three parts, each part containing an historical introduction. The first part contains a detailed account of [illegible]

[illegible] but no attempt has been made to discuss the clinical results, other than those made objectively on the various types of autonomic activity.

The second part contains a detailed account of the findings made post mortem and examined histologically. These findings are discussed in relation to the explanation of autonomic activity retained after sympathectomy in one area of the body. This part also deals with the probable explanations for autonomic activity retained in other areas after the appropriate sympathectomy.

The third part contains a more detailed account of observations on the changes in vasomotor innervation after sympathectomy. It is concluded with a discussion on the recovery of function after sympathectomy and with the author's suggested explanation.

As an assistance in reading, general conclusions are made at the end of each section, and a chapter on clinical applications has been added which summarizes the anatomical and surgical implications of the various types of sympathectomy in man.

An appendix contains details of apparatus which has been used in this research.

P. A. G. M.

CAMBRIDGE
October 1958

ILLUSTRATIONS

TABLES

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I AM very grateful to Mr D. W. C. Northfield, Surgeon-in-charge of the Neurosurgical Department, The London Hospital, for permission to examine patients under his care and for his continued interest and support during the progress of these investigations.

I am also very grateful to Professor J. D. Boyd, Professor of Anatomy in the University of Cambridge and lately University Professor of Anatomy at The London Hospital Medical College, for granting me the facilities of his Departments, for his constant advice and encouragement, and for assistance especially with the embryology, and for certain illustrations.

I also wish to thank Professor H. Barcroft, Sherrington Professor of Physiology at St Thomas's Hospital Medical School, for interest and advice in regard to observations on blood flow.

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I wish to acknowledge the kindness of other authors and publishers for their permission to reproduce a number of illustrations which are essential to the understanding of the text and which otherwise might not readily be available. These are:

Acta Psychiatrica et Neurologica Scandinavica (Ejnar Munksgaard Forlag) and Professor B. Rexed for Tables VI, VII and VIII; *Annals of Surgery* (J. B. Lippincott Co.) and Dr R. H. Smithwick for Fig. 22; *Archives of Neurology and Psychiatry* (American Medical Association), and Drs C. F. List and M. M. Peet for Fig. 59; *Brain* (Macmillan and Co. Ltd) for Figs. 2, 3, 54 and 55; *British Medical Bulletin* and Professor J. D. Boyd for Figs. 30 and 33; *Journal of Anatomy* (Cambridge University Press) for Fig. 61; *The Lancet* for Fig. 32 and also Dr T. Skoog for Fig. 73 and also Professor H. Barcroft and Dr G. T. C. Hamilton

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Numbers in the text printed in italic refer to a page or figure in another publication.

Part One

SWEATING PATTERNS AFTER SYMPATHECTOMY

Chapter 1

§1. HISTORICAL INTRODUCTION

The first reports of experimental observations on the peripheral distribution of the sympathetic nervous system appear to have been made by François du Petit in 1727. In dogs he sectioned the cervical sympathetic chain at the level between the 3rd and 4th cervical vertebrae and carefully noted that the effects were different from those obtained after sectioning the vagus. After sectioning the sympathetic he stated that the following effects were constantly to be observed in the eyes—

'... les Yeux sont devenus ternes, ils ont diminué, ils ont jetté de la Chasse ou des larmes, la Cornée s'est applatie, une membrane cartilagineuse qui coule sur le bord de la Cornée s'est étendûe, et en a couvert une partie, la Conjonctive s'est enflammée, &c. car nous supprimons un détail trop particulier.'

A facsimile of the original may be seen in the Frontispiece.

This account accurately describes the constriction of the pupil and protraction of the nictitating membrane, which are two of the principal signs by which paralysis of the cervical sympathetic chain may be recognized in animals. It is not clear that he recognized the associated enophthalmos, but the injection of the corneal vessels must be regarded as the first demonstration of vasodilatation consequent on section of sympathetic vasoconstrictor nerves. In a later account of this experiment by Claude Bernard in 1851, he does not comment on this aspect of du Petit's report.

Budge and Waller confirmed in 1851 that section of the cervical sympathetic trunk caused constriction of the pupil and that stimulation of the trunk would produce a dilatation of the pupil. According to Claude Bernard, the effects of electrical stimulation were first reported by Biffi in 1845. Budge and Waller showed that this autonomic control of the pupil could be traced to the 1st and 2nd thoracic segments of the spinal cord, and to this region they gave the name 'cilio-spinal centre'.

In the same year Claude Bernard (1851) gave his first account of vasodilatation produced when the cervical sympathetic chain was sectioned in the dog, horse and rabbit. In the following year (1852) he gave fuller details of the effects of such section. These comprised constriction of the pupil, retraction of the eye into its socket and a great activity in

the circulation in the whole of that side of the face, accompanied by increased warmth. In a later paper (1858—*page 237*) he went on to show that stimulation of the cervical sympathetic trunk caused a decrease in the circulation in the same area. Claude Bernard did not fully recognize the significance of his experiments. Meanwhile similar reports had also been made by Brown-Séquard (1852), who described the vasomotor paralysis with increased pulsation of the vessels following section of the cervical sympathetic, and the contraction of the blood vessels of the head when the cervical sympathetic chain was stimulated electrically. In this respect he makes the prior claim.

The signs of sympathetic paralysis in man were described by Horner in 1869, after whom the syndrome is now known. This consists of constriction of the pupil (myosis), drooping of the upper eyelid (ptosis) and supposedly enophthalmos, although recent work has shown that this is only apparent, rather than real, in man (Pochin, 1939). There is also vasodilatation and loss of sweating in at least the outer part of the face. It is of interest to record that Hare (1839) gave a clinical description of the syndrome in a case of tumour compressing the cervical sympathetic trunk.

Observations on sympathetic activity in the skin were made by Schiff (1870), who first reported pilo-erection in the tail of the cat on stimulating the sympathetic chain. Subsequently Luchsinger (1875) and Goltz (1875) showed that sweating was also under sympathetic nervous control. In 1878 Herman and Luchsinger demonstrated that sweat glands of mammals exhibited variation in electrical activity, and in 1886 Bayliss and Bradford demonstrated that electrical phenomena also accompanied the secretions in the skin of the frog.

These early observations were confirmed and extended by Langley (1891*a* and *b*, 1894), who worked out the origins of the sudomotor and vasomotor fibres to the foot of the cat from their origins in the sympathetic chain.

In the following years much work was done, principally by Langley and his co-workers, in determining the distribution of the sympathetic nervous system in animals. In 1922 some doubt was expressed by Burn in regard to the mechanism of sweat production, since after sympathetic denervation of the cat's foot, pilocarpine often caused increased sweating activity. Langley, however (1922), suggested that the action of pilocarpine was directly on the sweat glands. He also showed that a local injection of saline into the foot pad would cause slight secretion of sweat, and that if a solution of adrenaline was injected in a similar manner, sweat secretion would also occur—due to the saline content. It is interesting to observe, however, that Haimovici (1950) has recently suggested that there was evidence of adrenergic sweating in man—tested on the volar surface of the forearm, and also on the fingers, toes

and the forehead. Haimovici found that dibenamine—an adrenergic blocking agent—would prevent spontaneous sweating in these areas, but Chalmers and Keele (1952) showed by threshold injections of acetylcholine and atropine intradermally that all sweating in man is cholinergic. Kuno (1934) reported that the sweat glands are adrenergic in the sheep and the horse, but it appears that these are not innervated (Evans, 1957).

Clinical applications of Claude Bernard's discovery of the vasoconstrictor nerves were not made in this country for seventy years. Jaboulay (1899) appears to have been the first to suggest sympathetic denervation for cases of deficient blood supply to the legs, but had only recommended stripping of the femoral artery. It was the incidental observations of Hunter (1924) and Royle (1924*a* and *b*) which first suggested that sympathectomy would increase the blood supply to a limb. They had been sectioning the sympathetic rami in the treatment of spastic paralysis and found that it resulted in vasomotor paralysis. This observation was first made use of by Adson and Brown (1925), who performed lumbar ramisection and ganglionectomy, and perivascular neurectomy for the treatment of Raynaud's disease. They demonstrated the subsequent vasodilatation by means of skin temperatures.

Braeucker (1928) made the first observations on anhidrosis following sympathectomy.

A form of peripheral vascular disease affecting the digits had been described as early as 1862 by Raynaud and again in 1874. It is essentially symmetrical and, in the later stages, the pale or blue colour changes on exposure to cold are complicated by ulceration and even gangrene. The phenomenon is supposed to be due to vasospasm in the small arteries, which are abnormally sensitive to cold. Careful observations and clinical experiments were made by Lewis (1929), but the exact explanation is still not entirely understood.

In 1929 Adson and Brown made a further report on the treatment of Raynaud's disease by resection of the upper thoracic and lumbar sympathetic ganglia and trunks. In the same and following years Brown and Adson (1929 and 1930) gave careful accounts of the alterations in physiological activity of the sympathetic nervous system resulting from lumbar and cervico-dorsal (cervico-thoracic) ganglionectomies. They noted that vasodilatation was greatest in the extremities and that, in the lower limb, pilomotor reactions were absent in approximately the same areas as those in which sweating was absent. The local pilomotor reflex, however, was present to a variable degree on the shoulders and back where sweating, after cervico-dorsal ganglionectomy, was no longer produced. After this operation they reported that Horner's syndrome was present, but of variable intensity and persistence.

The observations of Brown and Adson on the anatomical distribution

of the sweating are of particular interest, not only because they appear to be the first to have recorded its patterns in man, following lumbar sympathectomy, but because their observations show sweating in the same dermatomes which, according to previous generally accepted ideas, were supplied by the same paravertebral ganglia as they had removed. Brown and Adson were familiar with the work of Kramer and Todd (1914) and Potts (1914) who demonstrated anatomically that the innervation to the skin arterioles corresponded to the innervation of the somatic segments. Brown and Adson's patients had undergone bilateral lumbar paravertebral sympathectomy L.2–L.4 inclusive, and were examined at intervals up to three years after operation. They tested sweating with the back of the hand, and in three cases by cobalt-blue papers, and also by the galvanic response produced by electrolytes in the sweat. The patients were first heated in a chamber until visible sweating occurred on the abdomen: in every case sweating had disappeared on the feet and lower part of the legs to a variable level at, or just below, the level of the knee. In the three cases which they examined more accurately, they showed that sweating was still present in the 2nd and 3rd lumbar dermatomes. In one case they observed that sweating was absent from the upper sacral area, as would be expected if the resection had included the lower level of the sympathetic outflow. This is now considered to be the 2nd lumbar nerve (or rarely the 3rd)—confirmed in man by Sheehan (1941) and Pick and Sheehan (1946). Brown and Adson do not seem to have recognized the significance of their observation that sweating persisted in the 2nd and 3rd lumbar dermatomes—the 1st lumbar paravertebral ganglia were left intact, and possibly they thought that these ganglia still supplied these areas by overlap. The true explanation, however, was not suggested for twenty years, until the author's own observations were made (Boyd and Monro, 1949).

Lewis (1930) and Lewis and Landis (1930) confirmed the physiological effects of cervico-dorsal sympathetic ganglionectomy. They showed that the patterns of loss of locally excited pilo-erection did not exactly correspond with that of loss of sweating. Similar observations were made by Wilkins, Newman and Doupe (1938) and by Bickford (1938). Simeone and Felder (1951) showed that sweat glands were no longer electrically excitable six days after nerve section.

Some of the confusion which had previously existed in regard to the chemical mediation of the sympathetic nervous system was explained by Dale in 1933. He introduced the classification of the autonomic nervous system according to the chemical substances liberated at the neuro-effector junction. He divided the autonomic nerves into two types 'cholinergic' and 'adrenergic'. The latter comprised the vasoconstrictor and pilo-erector nerve of the sympathetic, but the sweat glands were anomalous and he regarded them as being supplied with 'cholinergic

sympathetic' fibres. This hypothesis was confirmed by Dale and Feldberg (1934) who showed that acetylcholine was concerned in the chemical transmission of secretory impulses to the sweat glands of the cat.

Adson, Craig and Brown (1935) showed that essential hyperhidrosis could be cured by sympathetic ganglionectomy. List and Peet (1938*b*) have given an account of the anatomical distribution of disturbances in sweating resulting from lesions of the sympathetic nervous system. In a series of papers (1938*a*, *c* and *d*, and 1939), and List and Pimenta (1944), they had given a full description of the various aspects of sweat secretion in man. Most of their observations have been confirmed on numerous occasions by other workers, but some of these have reported observations on the distribution of anhidrosis following different types of sympathectomy. In view of subsequent work, the distribution patterns cannot have been accurately determined. Unfortunately, these inaccurate reports had caused considerable misconception in regard to the physiological effects which should have been expected after sympathectomy in man.

Roth (1937) examined twelve cases on whom Adson and Craig had performed lumbar sympathectomy L.1, L.2 and splanchnicectomy, and she stated that in these cases sweating was absent below the level of the groin. This is even more surprising in view of Brown and Adson's earlier report (1929) that in two cases it was absent only below the knees. In 1949, however, Roth and Craig made a subsequent report which partly corrected her earlier conclusions. They now thought that sympathetic denervation was incomplete in a large percentage of patients and that five to six months after sympathectomy the areas of anhidrosis were somewhat less extensive than immediately after operation. In 1945 Richter and Woodruff reported observations on the sweating patterns after lumbar sympathectomies. Because they found that these patterns did not agree with the levels of resections intended by the surgeons, they rearranged their patterns empirically and concluded that there must have been sympathetic dermatomes which were different from those observed by Foerster (1933). Most unfortunately, these patterns of Richter and Woodruff, which are now realized to be quite erroneous, are illustrated in current students' textbooks (e.g. Ranson, 1947—*page 108*, and 1953—*page 119*). In 1946 Richter and Otenasek reported their observations on the sweating patterns after cases of thoraco-lumbar sympathectomy. They completely omitted to examine for the presence or absence of sweating on the legs, although from the extent of the sympathectomies the lower lumbar and upper sacral dermatomes should have been rendered anhidrotic. In 1947, however, Richter (1947*b*) in a footnote to his paper on the cutaneous distribution of sympathetic nerves determined by the electrical skin resistance method,

first recorded that sweating was retained in the upper two or three lumbar dermatomes after thoraco-lumbar sympathectomy. No attempt at an explanation was made by him at this time. Ray and Console (1948), in an account of careful observations made on a number of cases after sympathectomy, confirmed almost invariable retention of sweating in the 1st and 2nd (and usually the 3rd) lumbar dermatomes. Ray and Console concluded that sympathetic pathways must exist which did not pass through any part of the paravertebral sympathetic chain. They suggested that the ganglion cells might be in the plexus around the aorta, behind the psoas muscle or in the lumbar nerves themselves, but it appears that they knew of no such ganglia in the latter situations.

Shortly afterwards, A. M. Boyd (1948) also reported his observations in England, but there was still no satisfactory explanation of this phenomenon. This account, however, prompted the author to investigate the cases being operated upon in the Neurosurgical Unit of The London Hospital, which led to the discovery by him and Professor J. D. Boyd of the significance of the intermediate lumbar sympathetic ganglia in the explanation of this phenomenon.

General confirmation of the sweating patterns after thoraco-lumbar sympathectomy, has been made by Wilson (1950) and Palumbo, Samberg, Hohf and Burke (1950). Thompson, Brose and Smithwick (1950) found that sweating was retained in the thigh, but accorded it an explanation which cannot be correct. They failed to observe that sweating was also retained in the central part of the face and in the perineum. Attention to the latter had been drawn by Ray and Console, and they had also recorded the former, although they had not commented upon it. The author will discuss later the sweating retained in both these areas.

Other aspects of the nervous pathways involved in sweating have recently been given by Johnson, Roth and Craig (1952*a* and *b*). They reported that after anterolateral chordotomy there may be some dissociation with the sweating and vasomotor patterns, but that sweating is retained in the central part of the face and in the perineum. Randall, Alexander, Coldwater, Hertzman and Cox (1952) had determined the sweating patterns on the lower extremity elicited by stimulation of the sympathetic trunk. They suggested that the segmental vasomotor distribution was different from that of the sudomotor and pilomotor fibres. The last two observations are in keeping with the hypothesis that the individual cells in the intermedio-lateral cell column of the cord mediate only one type of sympathetic activity, though their preganglionic fibres synapse with many cells (variously computed at twenty or so but probably many more) in the paravertebral sympathetic chain. It is the general experience of the author and other observers that resection of a portion of the paravertebral sympathetic chain produces a

loss of all forms of sympathetic activity in the skin of the corresponding dermatome. Where there is any discrepancy, this is discussed in the text relating to any particular case.

§2. THE DETECTION OF SWEATING ACTIVITY

The two principal methods for the detection of sweating activity in the skin depend on either the indication of sweat by its moisture content or the change in the electrical resistance of the skin. The former method is usually facilitated by the application of a dye which changes its colour in contact with moisture.

Eijkmann (1924) employed fuchsin: he painted the skin with an alcoholic solution of fuchsin and placed a piece of paper in contact with this area. Sweat dissolved the dye and stained the paper with red spots. Minor (1928) employed the colour reaction of iodine upon starch in solution, which produces a blue-black colour and is very convenient for photography. An alcohol and castor oil solution of iodine is painted on the skin and subsequently dusted with dried starch powder. This method was much used by earlier workers, but has the disadvantage that it stains the bed linen upon which the patient is lying. Brown and Adson (1929) employed cobalt-blue test papers which they applied to the skin in strips. These were originally deep blue in colour but, in contact with sweat, turned pink.

Kuno (1934), in his investigations on the physiology of human perspiration, measured the water content of the sweat directly, either by absorbing it onto filter paper and weighing the sweat absorbed or by evaporation by a current of dry air which was passed over calcium chloride. This was contained in U-tubes, of which he measured the increase in weight. Kuno did not use this method for the examination of any patients after sympathectomy.

Guttmann (1937, 1940*a* and *b*, and 1941) described another method which depends on the change in colour of a dye in contact with sweat. Guttmann used quinizarin, which is the sodium salt of chinizarin-2-6-sulphonic acid, and pinky brown in colour when dry but changes to a deep blue when moist. A fuller account of his method was given by Guttmann in 1947, although he first described the method in a German periodical in 1937. The author has employed Guttmann's method for the investigation of certain cases when the comparative degree of sweating is important. It is more convenient than Minor's method since it does not so easily stain bed linen, but has the disadvantage, common to all the chemical methods, that on the underside of the body, runnels of sweat from a sweating area on the upper side of the trunk or limb may obscure an anhidrotic area underneath.

Silverman and Powell (1944) have employed a tannic acid and ferric chloride method for recording the pattern of active sweat glands. Filter paper is first soaked in a 1 per cent. solution of tannic acid and then dried. A saturated alcoholic solution of ferric chloride is then painted on the skin and the filter paper placed in contact with it. Blue-purple spots mark the active sweat glands. The author has employed this method in an attempt to compare the numbers of functional sweat glands on the lower abdomen and on the front of the thighs after thoraco-lumbar sympathectomy (described later).

Koppanyi (1945) described a method of local estimation of sweating activity which depended upon the drug hexadienol. This he claimed to have a muscarine-like effect on peripheral cholinergic receptors. Unfortunately, supplies of this drug appear to be no longer obtainable either in this country or in N. America. Netsky and Walker (1947) and Netsky (1948) were able to show sweating activity directly by means of a glass prism placed in contact with the skin. Light was internally reflected by the prism, except where the sweat was in contact with the glass, and here the active glands would show as bright spots. By this method they estimated that 2 per cent. of sweat glands in the fingertip remained functional after cervico-dorsal sympathectomy. Subsequent local procaine injection into the ulnar nerve abolished this activity.

Randall (1946), Randall and Hertzman (1949), and Randall and McClure (1949) have employed a starch-iodine filter paper technique for measuring the activity of normal sweat glands. Randall and McClure, using weighed absorbent capsules containing filter paper, showed that normal sweat glands are not continuously active but discharge periodically. The preliminary response induced by increased ambient temperature is an increase in the number of functional glands. If this response is inadequate to meet the requirements of temperature control, further evaporative heat loss may be brought about by an increased output of individual glands.

Herrmann, Prose and Sulzberger (1951 and 1952) and Sulzberger and Herrmann (1954) have described a similar method using bromphenol blue as an indicator, previously used by Mentha (1949). They adapted this technique to give quantitative results by comparing the pattern and size of the dots on the filter paper against standards estimated by weighing methods.

Sutarman and Thomson (1952) have described a new technique for indicating the exact position of functional sweat glands. A plastic solution (2 per cent. to 4 per cent. w/v solution of polyvinyl-formol in ethylene dichloride containing 1 per cent. butyl phthalate as a plasticizer) is poured on to the skin. This dries quickly, and the impressions are detached with *Sellotape* and may be mounted on microscope slides. The presence of active sweat glands may be determined in their exact

relationship to the small creases in the skin. This would appear to be a most accurate method for investigating problems of sweat gland innervation. The author has commenced to use this technique but no results will be considered here.

Excellent reviews on the whole subject of sweating in man have been made by List (1948) and more recently by Evans (1957).

§3. THE ELECTRICAL SKIN RESISTANCE METHOD FOR DETECTION OF SWEATING

Lewis and Zotterman (1927) appear to have been the first to employ this method in man. In 1929 Richter gave a full account of the physiological factors involved in the electrical resistance of the skin. He employed the current from a low-voltage battery and measured it with a sensitive galvanometer. Various criticisms of this method have been made by McDowall (1933), who suggested that electrical resistance of the skin is possibly an indication of hyperaemia although it appeared that the resistance depends principally on the integrity of the stratum corneum of the skin. Goadby and Goadby (1936) pointed out that there are really two electrical phenomena: one depends upon the electrical potential and indicates sweat gland activity, but the skin resistance is a measure of vasodilatation. In practice, however, the passage through the skin of a small direct current affords a very precise method of measuring the activity of sympathetic innervation. Only a very small current will flow, indicating a high resistance, in skin that is not sweating. Darrow (1937) confirmed that the electrical resistance of the skin is a function of the intensity of sweating and is inversely proportional to it.

Richter and his co-workers (1927, 1942, 1943, 1945, 1946 and 1947*a* and *b*) have made many reports on this method for determining sweating activity. Richter and Whelan (1943) showed that in the cat the electrical resistance of the foot pad decreased in response to stimulation of the lumbar sympathetic ganglia. In 1946 Richter described a skin resistance meter which could be used for investigating peripheral nerve injuries, sympathectomies and paravertebral sympathetic blocks.

Jasper (1945) had earlier described a similar instrument, which employed a higher voltage battery and variable resistance in series so as to protect the sensitive microammeter should the electrodes be accidentally shorted. The author's apparatus has been redesigned on this principle, and it is described in detail in the Appendix.

Ratcliffe and Jepson (1950) described another electrical skin resistance meter which employed electronic amplification of very small currents. With this apparatus they did not believe it to be necessary to

heat their patients in order to determine the sweating patterns. This would appear to be a fundamental error, since their patterns do not show sweating on the anterior thigh in the majority of their cases of lumbar sympathectomy, when indeed this must have been present. The author has found it essential to heat his patients so that thermoregulatory sweating is evident in all areas to which the sympathetic pathways are intact. The difference in levels of skin resistance becomes much more precise after heating in this manner. If the patient is cold the method is not so reliable, although skin with an intact sudomotor supply still shows a slightly lower electrical resistance than that of sympathectomized skin. It has been the author's intention to show the changes in anatomical pattern after sympathectomy rather than physiological differences in the degree of activity in the sweat glands.

It has been shown by Richter and Otenasek (1946) and Boyd and Monro (1949) that very close agreement is obtained when using the chemical and electrical methods for examining sympathectomized patients, but that the latter is more sensitive. It is for this reason that the electrical skin resistance method has been used principally in this research. It has the further advantage that the underside of the patient lying in the sweating cabinet can also be examined for the presence of anhidrotic areas.

A description of the sweating test cabinet and its construction is given in the Appendix.

Chapter 2

TECHNIQUE AND EXTENT OF THE OPERATIONS ON THE SYMPATHETIC NERVOUS SYSTEM

In all, over fifty cases of various types of sympathectomy are considered in the examination of the sweating patterns following these operations. One case of injury to the brachial plexus is also studied, as this furnishes interesting information in regard to the growth of the postganglionic sympathetic neurones.

The operations were all performed at The London Hospital on patients who were in the care of Mr D. W. C. Northfield, Surgeon-in-charge of the Neurosurgical Department. There were 25 cases of thoraco-lumbar sympathectomy, 6 cases of four-quarter sympathectomy —that is, a combination of cervico-dorsal (cervico-thoracic) and lumbar sympathectomy—6 cases of cervico-dorsal sympathectomy, 6 cases of lumbar sympathectomy, and 11 odd cases including 4 cases of anterior rhizotomy. The 25 cases of thoraco-lumbar sympathectomy will be considered first, since they provide the most information in regard to the lower levels of outflow of the sympathetic preganglionic fibres, and it is from a study of these cases that an alternative pathway was recognized which did not pass through the paravertebral sympathetic chain. All the thoraco-lumbar cases were selected cases, inasmuch as they were all suffering from severe benign or malignant hypertension and their prognosis without operation was considered to be poor (Northfield, 1948). They were all seen by a physician before operation and assessment made of their renal function, cardiovascular system and cerebrospinal fluid. They were of both sexes and their ages lay between ten and fifty-two years. They were not found to be suffering from any neurological disease which would have affected the anatomy of the sympathetic nervous system. Initially, skin resistance measurements were made before operation on a few of the patients, but as no significant changes were ever observed this practice was later abandoned.

Originally the resection of the paravertebral sympathetic chain extended from the 8th thoracic to the level of the 3rd lumbar ganglion by a retro-pleural approach after a resection of the posterior portions of the 11th and 12th ribs. At later operations, the 8th and 9th ribs instead were resected, which enabled the surgeon to extend the operation upwards to the level of the 4th thoracic vertebra while still allowing him to reach down to the same level (L.3). The greater splanchnic nerve was

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at intervals for up to four years, and the patterns can be compared. The greatest interval between an operation and the observation of sweating pattern was in one case of lumbar sympathectomy which was examined twelve years after the original operation and in whom the pattern was found to be essentially similar to all other cases of lumbar sympathectomy which had been observed after a shorter interval. Included in these cases of thoraco-lumbar sympathectomy, the majority of which were performed by a retro-pleural approach, were also four cases performed by a transthoracic approach. This operation appears to be of an easier technique than the retro-pleural and is being performed more frequently in recent years. These four cases, however, suggest that it may often be imperfect and that ganglion cells may be left behind at different levels. The significance of the observations on these cases is considered later.

The six cases of combined cervico-dorsal and lumbar sympathectomy (four-quarter) were performed principally for Raynaud's disease affecting all four extremities. The operations were not all performed at the same time, and there was often an interval of several years between the lumbar or cervico-dorsal operation.

The six cases of lumbar sympathectomy usually had undergone a resection of the 2nd and 3rd lumbar ganglia—that is to say, that portion of the sympathetic chain overlying the 2nd and 3rd lumbar vertebrae.

As has been found by Pick and Sheehan (1936), there are usually only four lumbar ganglia and therefore there must be some condensation of the ganglia in respect to the vertebrae. Anatomically, of course, the ganglia should be described by their relationship to the grey rami communicantes, but these are not always evident at operation, and the levels given here are those of the apparent levels in relation to the vertebrae. From the functional point of view, section of the chain at the 2nd lumbar ganglion rather than the 3rd should make no difference—provided that the resection includes the lower level of thoraco-lumbar outflow of the sympathetic. This is usually from the 2nd lumbar nerve, though occasionally it may be from the 3rd lumbar in 10 per cent. of cases, according to Pick and Sheehan.

The six cases of bilateral cervico-dorsal sympathetic resection without combined lumbar sympathectomy were for Raynaud's disease except for one case of hyperhidrosis. They included three sides in which the operation was performed according to the technique described by Smithwick (1936). In this technique of so-called 'preganglionic' section, the 2nd and 3rd thoracic ganglia are divided from the lower part of the chain, and their rami communicantes from the 2nd and 3rd nerve roots are divided. These two ganglia are then brought up to lie in the wound in the muscle tissue. It has been suggested that in this way the postganglionic fibres and their cells of origin in the 2nd and 3rd thoracic

resected down to the level of the diaphragm, as was also the lesser splanchnic. The sympathetic chain itself was traced through the diaphragm, whose fibres were split in the process, so that the whole chain, from the level of the 4th thoracic vertebra to the 3rd lumbar vertebra with its splanchnic branches, could be removed in one piece. Silver clips were placed on the upper and lower ends of the chain that remained, so that subsequent X-ray examination would show the level of the actual resection. On the whole, these were seen to agree very closely with the levels intended. The levels referred to here are therefore those of the vertebral bodies. A clip placed at the level of the middle of the 4th thoracic vertebra is presumed to indicate that the 4th thoracic ganglion has been resected, whereas if it is only at the level of the disc between the 4th and 5th thoracic vertebrae, then the resection is considered to have extended only to the level of the 5th thoracic ganglion. In the lumbar region, of course, there is considerable variation in the arrangement of the gangliform enlargements of the chain, and there may be multiple rami communicantes connecting with several nerve roots as have been described by Fagarasanu (1938) and by Pick and Sheehan (1946). The purpose of extending the resection down to the level of the third lumbar ganglion rather than that of the 2nd lumbar, was in order to be sure that the lower level of the sympathetic preganglionic outflow was included. All the paravertebral ganglia below this level therefore, though they are still present in the body, should have been deprived of their preganglionic connections. As all but one case showed an absence of thermoregulatory sweating in the lower lumbar and upper sacral dermatomes, it is presumed that the resections were complete in this respect. In this one case, which is the only exception to the general observation of all cases, there may have been a double sympathetic chain present as has been described by Fagarasanu and by Pick and Sheehan, or possibly the resection was otherwise incomplete.

In the course of the operation there was necessarily a certain amount of trauma to the neurovascular bundle running below the resected ribs; this was indicated later by some cutaneous hyperaesthesia in this region, which, however, usually disappeared within a week or two of the operation. Similarly, cutaneous analgesia was present only in a small area on the inside of the curve of the incision, and this also showed normal sensation a few months later.

The operations were never performed on both sides on the same occasion. There was usually an interval of at least three weeks between the operations, and this was often increased. The patients were all quite willing for the sweating tests to be made on them, and the general purpose of these investigations has always been very carefully explained before they were performed. Many of these cases have been followed up

Chapter 3

§1. OBSERVATIONS ON PATIENTS

THE electrical resistance of the skin provides the most convenient and most sensitive method of determining the activity of the sweat glands. In this respect particular attention was paid to the assessment of the anatomical extent of sweating rather than to its relative quantity. Accordingly it seemed essential to induce free sweating in all areas which still retained the least amount of their sudomotor supply, though of course it was observed incidentally that some areas sweated profusely to the naked eye, whereas in others it could only be detected electrically. Only in a few special cases was a dye method employed to show differences in degrees of sweating. The patterns obtained by the electrical skin resistance method therefore show 'anatomical' areas rather than 'physiological' degrees.

Although in some of the earlier cases observations were only made upon the sweating activity of the sympathetic nerves, in all later cases observations were made simultaneously on the release of vasomotor control. It was therefore necessary to combine the two techniques. The most practical method of heating the patient was by hot air, as practised by Pickering (1932), since if immersion of a limb in hot water was employed, as suggested by Uprus, Gaylor and Carmichael (1936), then this would interfere with the measurement of sweating activity in this limb.

A plastic heating cabinet was designed to fit over an ordinary hospital bed, and contained in its roof a number of radiant-heat electric bulbs. The patient lay on the bed covered with a light blanket, and was exposed to dry heat until his body temperature was raised sufficiently to induce free sweating. Heating was continued until the patient's mouth temperature rose to at least 99·6° F. This took about half to three-quarters of an hour, but varied much with different patients and in the earlier cases took rather longer, due to insufficient heating being available. In general, heating must be continued longer with very fat or very fit patients: indeed, the greatest time for heating was required on a stocky young man with a brachial plexus lesion who had previously been a stoker on board ship. No advantage was to be gained by heating the patient to a higher temperature, since no apparent changes were made in the sweating pattern. Indeed, it was found that whereas some patients took a long time to reach 99° F., their subsequent rise in tem-

ganglia do not degenerate. As will be evident from tests described later and carried out on these cases, there is no reason to believe that such ganglia survived and it is apparent that the ganglion cells died as would be expected. The remainder of the cervico-dorsal cases were all operated on by ganglionectomy which included the stellate ganglion. Although the term 'stellate' is usually applied only to the fused inferior cervical and 1st thoracic ganglia in animals, it seems apparent that this fusion is the more common form in man as well, and is so referred to in more recent papers, White, Smithwick and Simeone (1952—*page 28*), and Jamieson, Smith and Anson (1952) found such fusion in 82 per cent. of 100 human dissections. The resection of the stellate ganglion was always combined with that of the 2nd thoracic ganglion and sometimes also with the 3rd thoracic ganglion. When the 1st thoracic or the inferior cervical ganglion is resected, the patient always shows a Horner's syndrome. This is evident by the drooping of the upper eyelid (ptosis) and constriction of the pupils (myosis). When the 1st thoracic ganglion is left intact there is usually no Horner's syndrome.

The eleven odd cases whose sweating patterns are of particular interest include one case who had multiple operations for sympathectomy of the upper limb, and upon whom finally the 1st thoracic anterior nerve root was sectioned. There is also one case upon whom a section of the whole 1st thoracic nerve root was performed for a neuroma, and a case upon whom the 2nd to 5th thoracic nerves inclusive were sectioned at thoracotomy. The four cases upon whom anterior rhizotomy was performed were all suffering from painful flexor spasms due to disseminated sclerosis. It is probable that these cases also had a degeneration of the lower motor neurone, but they were all examined before operation and no areas of anhidrosis were detected. One case of brachial plexus avulsion is included, as this is instructive in showing the variation in pattern of recovery of sensation to the skin and of recovery of autonomic innervation to the sweat glands and to the blood vessels. The recovery of vasomotor responses is considered later and is particularly interesting when compared with the findings after ordinary sympathectomy.

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perature was much quicker and care had to be taken that they were not heated unduly and thus unnecessarily distressed. The air temperature in the cabinet reached about 45° C. (113° F.) and fresh air from the room was allowed to diffuse in between the edges of the cabinet and the bed-clothes.

On those cases who had undergone cervico-dorsal sympathectomy, and upon whom observations on the blood flow in the fingers were performed simultaneously with the heating of the patient, their hands protruded through portholes in the cabinet into the air of the room outside. The forearms, as they passed through these portholes, were sealed by blankets placed inside the cabinet, and in such cases it was found that the temperature of the air around the hands only increased by 2° or 3° C. after three-quarters-of-an-hour's heating in the cabinet. Cases which had undergone lumbar sympathectomy for peripheral vascular disease and upon whom observations on blood flow in the great toe were made, usually protruded their legs beneath a half-section of the cabinet at the level of the knees so that the lower legs and feet were exposed to the outside air. In the cases of the thoraco-lumbar sympathectomy, however, it was found more convenient to keep the whole body inside the cabinet. Blood flows in the great toes were obtained with the cups of the plethysmograph included within the cabinet, and therefore in these cases the feet and toes were at least at the temperature of the air in the cabinet.

Patients who had undergone a thoraco-lumbar sympathectomy for hypertension were never very fit even before operation. After operation they are losing heat from their autonomically denervated and dilated peripheral vessels and frequently have a subnormal temperature. The first examination was at the most convenient time after operation, which was always after the skin sutures of the wound had been extracted and dressings removed. Some of the other patients had to be examined as early as two weeks after the operation, but later on efforts were made to delay testing, usually until after a short period of convalescence. It was found, however, that patterns obtained after operation on the first side only were very similar to those obtained a few weeks later after the second operation, when the same side was tested again. The borders of the sweating areas usually could be marked more precisely at the second examination. Ray and Console (1948) report that they examined some of their patients as early as the fifth day after operation and that they noted smaller areas of residual sweating than they did a few days later. They thought that a period of 'readjustment' occurred until the pattern

a profound fall in blood pressure, and it would seem doubtful whether all sweat glands would respond normally even though they still retained their preganglionic and postganglionic innervation. No attempt was made, therefore, to test patients before the end of the second week, as it was considered that even if any results were obtained they might not have a true anatomical basis. Subsequent observations were made at approximately yearly intervals and depended upon the patient's ordinary appointment for follow-up after operation.

Some of the earlier patients were given a hot drink when the heat was turned on in order to reduce the total heating time. Aspirin 10 gr. (0·65 G.) was also given by mouth to these patients, since this drug is supposed to have a sudorific action only by its central effect. Later, patients upon whom blood flow measurements were made simultaneously were never given anything by mouth in case this should invalidate the blood flow observations.

Similarly, pilocarpine or other parasympathomimetic drugs were not administered for testing thermoregulatory sweating, since it was considered that they would produce sweating in areas which still retained a postganglionic nerve supply though the preganglionic supply to these cells had been severed. Special testing, however, was performed with the drug carbachol, which will be described later. Adson and Brown (1929) observed that after pilocarpine, sweating occurred in certain patients in areas which were previously dry after heating. There has been much discussion in the literature since that time and many controversial results have been published, such as by Richter (1927), Hyndman and Wolkin (1941) and Hyndman, Wolkin and van Allen (1948) using similar parasympathomimetic drugs. The author (Boyd and Monro, 1949) has discussed observations on the action of such drugs and suggested an explanation. The sweating patterns obtained after injection of carbachol on some of these patients have been given elsewhere (Monro, 1950*b*), and the results of these tests are described in the individual analyses of the sweating patterns obtained on these patients.

§2. METHOD OF TESTING

When the patient is sweating sufficiently, some of the heat bulbs are turned off and the observer enters under a side flap of the cabinet; and in order to conserve heat a blanket is arranged to curtain the gap between the edge of the flap and the bed. The pointer electrode of the skin resistance meter is drawn slowly over the skin of the trunk from an area of high resistance (non-sweating) to an area of low resistance (sweating). When the galvanometer registers a greater flow of current, a mark is made at that point on the skin with a fountain-pen filled with a pro-

prietary washable ink. In this way the upper and lower edges of a non-sweating area can be mapped out and the points joined with a continuous line. The boundaries of the area on the legs or arms can be mapped in a similar manner, and the patient is then turned to right or left in order to map the back. Even though runlets of sweat may encroach onto a non-sweating area, the true pattern is easily apparent after the sweat has been wiped away. The boundaries of the upper lumbar dermatomes, where they are contiguous with the sacral, are particularly precise.

In several cases, the pattern of the area of low electrical skin resistance was confirmed by a chemical test for sweating. Quinizarin powder was applied to the skin before heating. The purple colour produced with sweat extended to within about one centimetre of the area of low electrical resistance. The latter method was therefore more sensitive and had the advantage also that it could be determined on the underside of the patient's body.

In general it is found that after a thoraco-lumbar sympathectomy extending from the level of the 4th thoracic to the 3rd lumbar segment, a typical patient will show the following pattern of thermoregulatory sweating. Sweating is absent in a belt around the lower thorax and upper abdomen, corresponding to the dermatomes T.5–T.11. It is profuse over the lower abdomen, groin, pubis, front of perineum and upper buttock; and less profuse, but quite definite, on the front of the thigh and inner side of the calf—corresponding to dermatomes T.11–L.3. It is absent again on the front and outer side of the leg below the knee, on the foot, and on the back of the leg up to the lower buttocks—that is, on L.4–S.2 dermatomes. It is present again in the perineum, around the anus, on the back of the scrotum or the sides of the labia majora, and in the groin where it adjoins the inner side of the thighs—corresponding to the 4th sacral and lower dermatomes. This area around the lower trunk and extending down on the front of the thigh is a constant feature and is hereafter referred to as the escape area, since it evidently escapes the sympathetic denervation that was intended and therefore must be supplied by alternative sympathetic pathways.

There may be 'islands' or 'peninsulas' of sweating, or of non-sweating, in certain areas which have quite an irregular pattern. If the resections of the paravertebral chain have been made to the same level on each side, the lower border of sweating around the trunk is usually precise and symmetrical. The upper border of sweating around the abdomen, however, is often asymmetrical and irregular, whereas the lower border at the knees and thighs though usually fairly symmetrical, is not so precise in outline. Small islands of sweating can often be recognized on the inside of the calf extending along the general course of the saphenous nerve, but never below the medial malleolus of the ankle. The degree of

sweating on the front of the thigh is certainly less than before operation, which suggests that there is a partial denervation of the sweat glands in this area. It is also possible that these areas are supplied by overlap from the segment above. Attempts to measure the amount of sweat produced in different areas before and after sympathectomy were made by the tannic acid paper-ferric chloride method (Silverman and Powell, 1944). In two patients who were examined several weeks after thoraco-lumbar sympathectomy on one side, but before that on the other, it appeared that on the front of the thighs in the 2nd lumbar dermatome there was definite diminution of the number of functioning sweat glands and also the amount of sweat secreted by each gland which remained functional. Possibly a more elaborate method such as that of direct estimation of the weight of sweat secreted over unit area (Randall and McClure, 1949; Kuno, 1934) or the pattern produced on a plastic sheet (Sutarman and Thomson, 1952) might give more information in this respect.

After the boundaries of the sweating areas were marked with a proprietary washable ink they were drawn freehand onto special charts which showed the four standard body outlines of the front, back and side views, and also special views of the perineum and the extremities. Some of these designs were portrayed by Richter (1946). The charts were completed with observations on precision of the borders of the sweating areas, the dates of operation, temperature of patient and other relevant information.

The ink marks on the patient were then strengthened with a ¼-inch band of the dye *Xylene Cyanol, FF* 2 per cent. in spirit. This dye is an intense blue in colour and dries immediately—and, unlike gentian violet, it washes off again very easily and does not stain the bedding. The patient can then be photographed either in the room where he has been examined or, later, in the photographic department. Four views are taken with the arms away from the body. In the side views the patient stands with the more distant leg in front—so as to show the inner side of the thigh and calf.

The photographs provide a more exact record of the sweating areas than do the freehand drawings, and they can therefore be used to compare the patterns obtained at successive examinations. For reproduction purposes the patterns on the photographs are redrawn onto standardized figure outlines, special attention being paid to the segmental values of the original sweating areas. These are then shaded in red crayon to indicate the anhidrotic areas. In the illustrations the initials of the patient, the extent of sympathectomies and intervals since operation are marked beneath each figure.

The general pattern of anhidrosis after cervico-dorsal sympathectomy which includes the stellate and 2nd thoracic ganglion is, on the whole,

quite constant shortly after operation. On the trunk the lower level of anhidrosis extends over the distribution of the supraclavicular nerves—that is, down to about the 2nd intercostal space. On the back it is at rather a higher level, depending on whether the resection includes the 2nd or 3rd thoracic ganglion. The whole arm is anhidrotic except for an area in the axilla extending into the upper part of the under arm, and anhidrosis extends over the head and neck, with two exceptions.

The central mask of the face, which includes an area on the forehead just above the eyebrows, around the eyes and the sides of the nose, and around the upper and lower lips, constantly retains sweating activity. In about half the cases sweating activity remains in a small patch in front of the neck over the larynx and also behind the lobe of the ear, and on the lobe of the ear extending towards the external auditory meatus. The significance of these patterns will be discussed later.

After lumbar sympathectomy the general pattern of anhidrosis extends on the outer side and back of the leg, but not including the front of the thigh, inner side of knee, calf or ankle. It thus includes the 4th and 5th lumbar, and 1st and 2nd sacral and, possibly, the 3rd sacral dermatomes. The 4th and 5th sacral dermatomes in the perineum are found to be sweating. It does not seem to be significant whether or not the 1st lumbar ganglion is included in the lumbar sympathectomy. Possibly the degree of sweating in the lower part of the abdomen, groin and upper thigh (1st lumbar dermatome) may be slightly less if the 1st lumbar ganglion is resected, but, contrary to the claims of Ratcliffe and Jepson (1950), there would appear to be no advantage in extending the lumbar sympathectomy above the 2nd lumbar ganglion. The result, of course, would be similar to that of thoraco-lumbar sympathectomy and general patterns of sweating confirm this.

§3. CARBACHOL SWEATING TEST

After it became apparent that the lumbar intermediate sympathetic ganglia were responsible for supplying the sudomotor fibres to the escape area, a survey of the reports of Hyndman *et al.* (1948) and their criticism of Ray and Console's paper (1948) suggested that some confirmative tests might strengthen the argument in regard to the function of these ganglia. Hyndman and Wolkin (1941), while examining patients after cervico-dorsal sympathectomy, had used a pharmacological test which had originally been suggested by List and Peet (1938*c*) as a method for distinguishing between preganglionic and postganglionic innervation of the sweat glands. They observed that if the ganglion cells and postganglionic fibres were intact, which they should be if only the preganglionic fibres were divided, then injections of parasympatho-

mimetic drugs, such as pilocarpine or mecholyl, would continue to cause sweating in areas which no longer showed thermoregulatory sweating. In their opinion this was produced by the local action of the drug on the neuro-glandular junction (end plate), and there has been experimental confirmation of this in the cat by Simeone, Mentha and Rodrigues (1951).

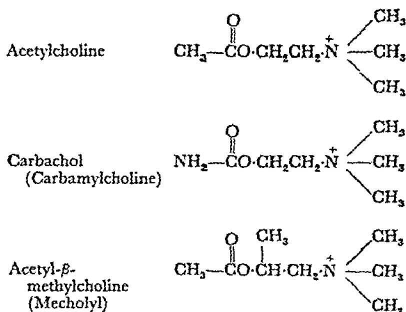
It was therefore considered that a similar drug—carbachol—should be able to produce sweating in these patients in the dermatomes below and including the level of L.4. These lower paravertebral ganglia (and the intermediate ganglia from the same nerve roots) remain intact after resection of the sympathetic chain down to the level of the 3rd lumbar ganglion—which has included, of course, all the preganglionic fibres from the lower end of the sympathetic outflow. In the anhidrotic area on the thorax, however, all the sweat glands should have suffered a postganglionic denervation, since the paravertebral ganglia had been resected at these levels. An injection of carbachol therefore should produce sweating all over the body except in areas which have suffered a postganglionic denervation. Such a test was found to fit this hypothesis. Sweating appeared on all the body below the upper border of the escape area, and the thoracic anhidrotic area was practically unchanged.

The carbachol sweating test was not performed as a routine on all cases, but was carried out on a number of patients on whom it was thought likely to yield additional information. The test is performed immediately after the heating test, though precautions must be taken to prevent the patient becoming too cool in the meantime.

It appears that patients do not respond equally to the same dose of the drug. Possibly this is due to different rates of absorption or to differing susceptibilities. In order to standardize its action as much as possible, carbachol was given as an aqueous injection of 0·25 mg. in 1 ml. (1 ampoule) into the quadriceps muscle mass and the reaction noted. Usually within ten to fifteen minutes this would produce a desire to micturate and possibly, if the rectum were full, to defaecate. Shortly afterwards it would be found that the electrical skin resistance in the sacral anhidrotic area had now been reduced, but no change had occurred in the anhidrotic area on the thorax. If no symptoms from the drug had been produced within twenty minutes, another $\frac{1}{2}$–1 ampoule (0·125–0·25 mg.) was injected and, if necessary, a third—when such symptoms would almost certainly be produced. In very small or frail patients the initial injection was made with only $\frac{1}{2}$ ampoule (0·125 mg.). Occasionally it was found that the estimate for the initial dose was too large (or the patient had an undue susceptibility), and the patient would soon have severe or colicky pain and vomiting, and would feel much distressed—though this would soon respond to a small injection of atropine $\frac{1}{100}$ gr. (0·6 mg.) subcutaneously.

The intention was to grade the dose to suit the patient so that definite sweating was produced in those areas which were known to retain their postganglionic innervation. In rare cases, however, this could not always be produced on the sole of the foot, though it is probable that if the dose had been increased, sweating would have been produced here also—but the patient would have been caused considerable distress. Even in those cases when too large a dose was given inadvertently, the pattern of anhidrosis obtained on the thorax was essentially similar to other cases which did not show severe symptoms.

Hyndman *et al.* (1948), when using *Mecholyl* (methacholine chloride) acetyl-β-methylcholine chloride, reported that they did not obtain the above patterns but they were using a chemical type of sweat detector which was not so sensitive. Carbachol, however, is a drug which has a chemical structure more similar to acetylcholine, than has mecholyl.



The actions of carbachol resemble those of acetylcholine and include both nicotine actions and muscarine actions, whereas mecholyl has only muscarine actions (Gaddum, 1953—*page 191*).

It may be, therefore, that carbachol acts both on the pre-post-ganglionic synapse (or on the ganglion cell directly) as does acetylcholine (nicotinic action), whereas pilocarpine and mecholyl act only on the neuroglandular junction (end plate). Possibly, therefore, it is for this reason that carbachol produces a more definite sweating pattern than does mecholyl. In any event the patterns it produces are anatomically sound.

The slight differences in the patterns of anhidrosis on the thorax which are obtained after heating and after carbachol will indicate those areas of skin which may still be innervated by sympathetic ganglion

cells in the thorax, although the preganglionic fibres to these cells have been interrupted by operation. The pattern of anhidrosis obtained after carbachol always lies within that obtained by heating alone. After an injection of carbachol the lower border of the anhidrotic area on the thorax will be raised if there remain *in situ* any intact ganglion cells, which have been deprived by the operations only of their preganglionic connections. Thus the upper border of the escape area will extend upwards if this area of the skin is supplied by ganglion cells lying in the intermediate sympathetic ganglia, and whose preganglionic fibres have passed through the thoracic paravertebral sympathetic chain.

It is possible that if any ganglion cells of the paravertebral sympathetic chain had also been left behind, owing to incomplete resection of the chain, then after an injection of carbachol they would also produce sweating in parts of those dermatomes. Processes of the paravertebral ganglia, which contain ganglion cells, may extend for a short distance along a ramus communicans back towards the nerve root. They have been described by Wrete (1935 and 1943), Fagarasanu (1938), Pick and Sheehan (1946) and Edwards (1951). They will be discussed more fully later. They would function in exactly the same way as lumbar intermediate sympathetic ganglia whose preganglionic nerve supply had been interrupted.

Carbachol sweating on cases after cervico-dorsal sympathectomy yields a much less constant pattern. Usually the whole of the face, head, neck and upper limbs show some degree of sweating activity, except for roughly segmental patches on the underside of the arms—particularly those dermatomes supplied by the lower roots of the brachial plexus. In those patients whose operation had been performed by the anterior approach through an incision extending parallel to and above the middle part of the clavicle, the supraclavicular nerves had been divided and usually it was found that the area of skin below this, extending down to the 2nd or 3rd intercostal space, remained anhidrotic after carbachol injection.

Chapter 4

DERMATOME PATTERNS AND ANALYSIS OF INDIVIDUAL SWEATING AREAS

Before it is possible to consider the individual analysis of the root values of the sweating patterns, it will be necessary to discuss the dermatome patterns in man. The first accurate account of these dermatomes in man was proposed by Head in 1893. He obtained his observations from the disturbances of sensation, with special reference to pain of visceral disease, and also from the distribution of herpes zoster infection affecting a posterior root ganglion. In a later paper with Campbell (1900) he went on to show the close association of zoster infection of a single posterior root ganglion with the production of herpes in the area of his proposed outline of the dermatome corresponding to that nerve root. The dermatomes of Head are shown in Fig. 3 and should be compared with the later observations of Foerster (1933) shown in Fig. 2.

Foerster's observations were all obtained on patients upon whom he operated for different conditions by sectioning the posterior nerve roots intra-spinally. These operations are no longer performed for these conditions because of the ill-effects which became apparent to later observers. Foerster stimulated a number of the posterior nerve roots and recorded the pattern of the antidromic vasodilatation (first described by Stricker in 1876), and also tested the patient's sensation to light touch and pain, following section of numbers of contiguous nerve roots. In many cases he left one intact posterior nerve root and sectioned three or four nerve roots above and below it, so that he was left with an area of residual sensibility to the intact nerve root. In other cases he resected a group of contiguous nerve roots and was able to determine the upper or lower levels of sensation via the intact roots above or below.

Other observations on man had been obtained directly by Bolk (1898–1899) who laboriously dissected the filaments from separate nerve roots into the skin. In view of his technique, it is extraordinary how accurate some of his dermatomes eventually proved to be when compared with those of Foerster and Head. Unfortunately, however, they appear to be incomplete in certain areas and therefore cannot be regarded as a reliable pattern, although they can provide interesting topographical confirmation of the clinical and physiological observations.

Sherrington first proposed a system of dermatomes for the macaque

monkey in 1892, and in two following papers, 1893 and 1898, he reported the results of his experiments on the macaque in regard to the areas supplied by certain individual posterior nerve roots. The first paper dealt with the supply to the lower limbs, and the second paper to the upper limbs. He also found a considerable overlap of the dermatomes, and his general pattern compares very closely with those of Head and Foerster, particularly of the latter when allowance has been made for the slight skeletal difference between man and the macaque.

Keegan (1947) and Keegan and Garrett (1948) discuss the patterns obtained by these three authorities for the upper and lower limbs in man, and compare them with their own observations on the area of principal innervation which they found by measurements of the hypoalgesia resulting from compression of a nerve root by a prolapsed intervertebral disc. Some of these cases they verified by surgery, and in some cases the nerve roots were sectioned, and in others X-ray controlled single nerve root injections of local anaesthetic were made into volunteers. In general, their patterns of the principal innervation of the dermatomes which are everywhere contiguous and do not overlap, all lie within the patterns of 'residual sensibility' of the dermatomes as found by Sherrington, Head and Foerster. In his paper Foerster shows some individual variation in the same dermatome in different patients, and even some discrepancy between that of antidromic vasodilatation and of residual sensibility of the same root in the same patient. The diagram shown in Fig. 2 has been redrawn by the author from the data of Foerster's paper (1933). It will be noted that Foerster gives no information on the 7th cervical or lower sacral dermatomes, nor of the posterior portions of the thoracic dermatomes. The first cervical nerve has no cutaneous branches.

It will be seen that Foerster's dermatomes are in general agreement with those of Head, except for a rather greater extent and overlap of each dermatome in the limbs. On the trunk it will be noted that the dermatomes are segmentally and alternately contiguous, so that each area of skin is supplied by at least three posterior nerve roots. The area of the umbilicus, for instance, lies principally on the 10th thoracic dermatome, but is also included in the lower edge of the 9th thoracic and the upper edge of the 11th thoracic. In the limbs this overlap seems to be of greater extent, so that at the wrist (for instance) portions of sensory nerve root innervation from the 5th cervical to the 1st thoracic may all be included. On the buttock it will be observed that the 1st lumbar dermatome extends to become a continuous curved band, but that the 2nd lumbar dermatome may be in two portions; that nearer the mid-line being supplied by the posterior primary division, and that on the front and outer aspect of the thigh by the anterior primary division. There may be a similar supply of the 3rd lumbar dermatome.

Although Head shows patterns of the lower sacral dermatomes, it appears that this information was based on only one case directly, and there does not appear to be absolute confirmation of the pattern that he shows.

It will become evident that the patterns of residual autonomic innervation of the skin after sympathectomy tend to fit closely the general

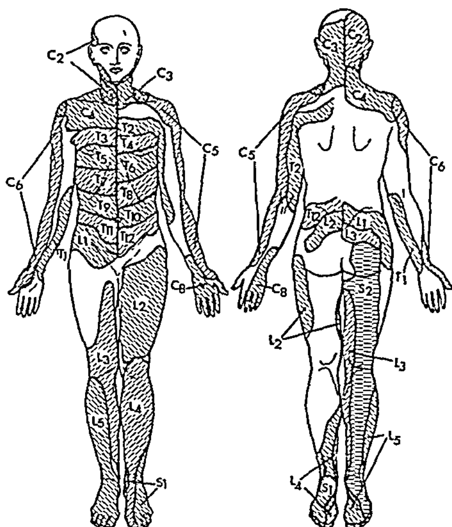


FIG. 2. Dermatome chart, constructed from observations of Foerster (redrawn). Foerster, O. (1933), *Brain*. The 7th cervical, posterior thoracic, and lower sacral dermatomes not recorded.

patterns of the posterior root dermatomes described by Foerster. The only other claim for autonomic dermatomes was made by Richter and Woodruff (1945), who showed a very idealized form of lumbar autonomic dermatomes. It is now evident that the patterning they suggest was based on a complete misconception of what they were observing and, indeed, in later papers by Richter (1947*b*) on this subject he makes no further reference to this original paper.

In the following account of the individual analysis of the sweating patterns, reference will be made to the dermatome chart constructed from observations of Foerster (Fig. 2), and the general outline of the dermatomes so marked will be considered in relation to the patterns obtained by observation on these patients. Of course, individual variation may be considerable in relation to the exact margins of a particular

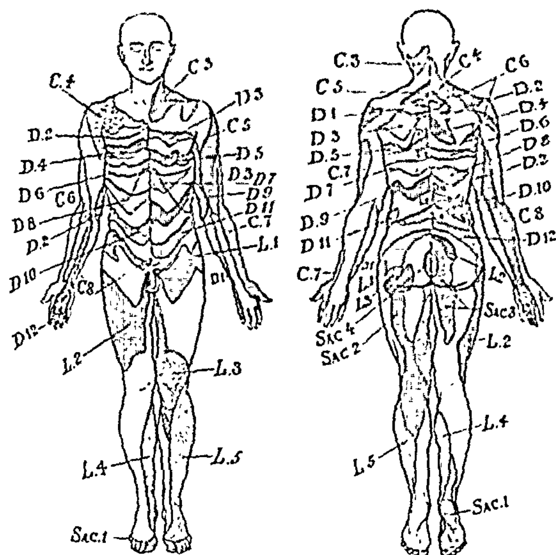


Fig. 3. Dermatome chart, according to Head. Head, H., and Campbell, J. W. (1900), *Brain.*

dermatome, and allowance for this is made in discussing the patterns obtained after sympathectomy. Indeed, as the author's cases comprise a far larger series of observations in relation to certain particular dermatomes, it may be argued that the variations between one patient and another are evidence in support of the overall variation of such a dermatome, rather than for including a particular area in a different dermatome, which would be otherwise inconsistent with the apparent levels of sympathectomy.

Another factor which is to be considered is the general level of pre-fixation or post-fixation of the brachial or lumbo-sacral plexi. The frequency of this variation does not appear to have been examined in man, but according to Sheehan and Marrazzi (1941) on the monkey post-fixation may occur in about 25 per cent. of cases. These general results are confirmed by Zuckerman (1938), who found, again in the monkey, that the frequency of pre-fixation of the lumbo-sacral plexus was more common (56 per cent.) than post-fixation of a plexus (23 per cent.). On the same cases he found that the lowermost 'white' ramus communicans was at the level of L.3 in 47 per cent., L.4 in 51 per cent. and L.5 in 2 per cent.

The author's observations on the level of anhidrosis after thoraco-lumbar and lumbar sympathectomy would suggest that for man the lower levels of the thoraco-lumbar outflow were at L.2 in 14 per cent., L.3 in 85 per cent. and L.4 in 1 per cent. Among those included in the L.3 group, 32 per cent. of the total tended to have a lower extension than the other 53 per cent. As is to be described more fully later, one case fitting into the L.2 group was found, on dissection later, to have a 'pre-fixed' type of lumbar plexus.

Chapter 5

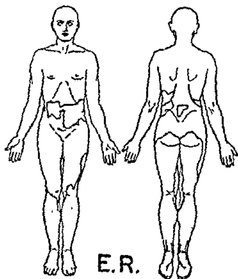
§1. SWEATING PATTERNS AFTER THORACO-LUMBAR SYMPATHECTOMY

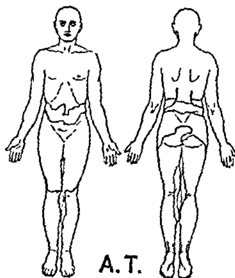
FIG. 4 shows six typical patterns of sweating tests after thoraco-lumbar sympathectomy.

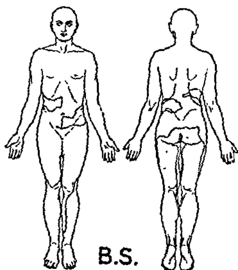
CASE L.R. shows the result of resection extending from the T.8–L.3 sympathetic ganglia on each side and followed up at 10 and 8½ months after left and right sides respectively. It will be seen that the belt of anhidrosis on the lower thorax and upper abdomen is not complete on the back, although there is a small 'island' over the upper lumbar spines. The upper level of the anhidrotic area extends approximately to the T.8 dermatome on the left and to T.9 on the right. That is to say, that it appears that the 8th and the 9th thoracic sympathetic ganglia respectively are non-functional, leaving those of the 7th on the left and the 8th on the right intact, and it is the lower level of these dermatomes which provide information on the upper level of apparent resection of the ganglionic chain. The upper level of the escape area is not so high on the left as it is on the right. On the left it appears to include the L.1 dermatome, but on the right side it extends upwards to include the T.11 dermatome. The lower levels of the escape area extend about equally below the inner sides of the knees into the L.3 dermatomes. It will be noticed that there is a 'peninsula' of sweating extending from the escape area on the right side towards the umbilicus. This was one of the earlier cases and no plethysmographic records were performed.

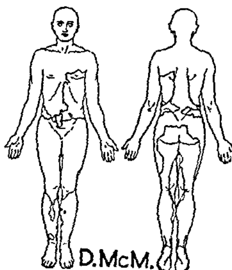
CASE A.T. shows the pattern obtained in a similar case of resection from the T.8–L.3 ganglia on both sides. This case is more symmetrical and shows the upper level of the anhidrotic area extending to the T.9. dermatomes on each side. The escape area is also more symmetrical and extends upwards to the T.12 dermatomes on each side and down to include the third lumbar dermatomes below the inner sides of the knees. It will be noticed that there is a 'peninsula' of sweating extending down to the umbilicus just to the left of the mid-line, and that on the right side of the buttock sweating is continuous with that in the perineal area. No plethysmographic observations were made on this patient.

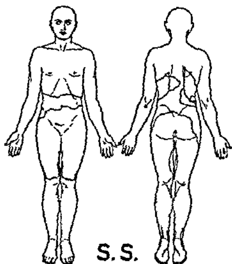
CASE B.S. Although this was one of the earlier cases, and had a resection from the T.9 ganglion on the left and T.8 on the right, both extending down to L.3 ganglia, it was not followed up until 4½ years after operation. It will be seen that although the intended levels of resection are approximately the same, the sweating pattern resulting is markedly asymmetrical. On the left side the upper level of the anhidrotic area is at about the T.9 dermatome, whereas it is two segments higher, reaching the T.7 dermatome, on the right. Similarly, the upper level of the escape area is only at the level of the L.1











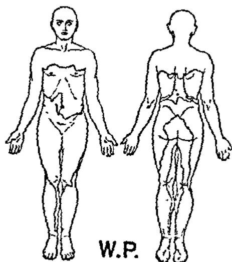


FIG. 4. Cases E.R., A.T., B.S., D.McM., S.S., W.

dermatome on the left, whereas it extends well into the T.10 dermatome on the right. In view of the results of later cases this might suggest the possibility of a T.11 or T.12 ganglion being left behind at operation, as the chain passes through the crus of the diaphragm on the right side. The lower level of the escape area does not extend below the knee on the right side—that is, only into L.2 dermatome—but on the left side it extends well down the inner side of the calf into the L.3 dermatome.

Plethysmographic observations carried out on this patient, at this time, suggest that there was a slight recovery of autonomic vasoconstrictor control on the right side. There was slight increase of blood flow in the right toe on heating the patient, and very slight increase of the pulse rate on the left.

CASE D.M.M. Although in this case the resection on both sides was intended to reach the level of T.4, and appears to have done so on the left—even extending one segment higher—on the right it does not extend much higher than T.9. Also, both in front and behind there are small gaps connecting the normal area with the escape area. The upper level of the escape area extends apparently to L.1 dermatomes on each side, and well down into the L.3 dermatomes on the inner sides of the legs. It should be noticed that a combination of lower paramedian and pararectal (Battle's incision) scars extended the area of anhidrosis down into the strip of skin between them. There is evidence of similar partial denervation medial to a pararectal scar in Case W.P. and possibly also in Case L.C. (Fig. 8). No plethysmography was performed on this patient.

This patient developed a peculiar condition of ischaemia and gangrene on the right leg after operation on that side, and it is probable that the small area of low electrical skin resistance on the front of the right lower leg may really be due to local trauma.

CASE S.S. Although the resection on this case was intended to extend as high as T.4 on the left and T.8 on the right, it is obvious that the upper level of the anhidrotic areas are approximately equal and reach the T.7 dermatomes on each side. The back view suggests that it might have been slightly higher on the right, but this is probably due to injury to the intercostal nerves at the upper end of the skin incision. Again the belt of anhidrosis is incomplete behind. The upper level of the escape area is asymmetrical, extending upwards only to the L.1 dermatome on the right but higher, on the left, to the T.12 dermatome. The significance of this will be discussed later. The lower level of the escape area is symmetrical, and extends only to the level of the knees at the L.2 dermatomes on each side. On the right there is a small 'peninsula' of anhidrosis extending down over the anterior superior iliac spine and the upper outer aspect of the thigh, which is possibly due to trauma of the ilio-hypogastric nerve. There are also small islands of sweating on both sides of the thoracic anhidrotic area. This was one of the earliest cases and no plethysmographic observations were made.

This patient died two months after these tests, and subsequent post-mortem examination was made. This is discussed in full later (Chapter 9), but it may be noted now that the nerve roots conformed to the 'pre-fixed' type of lumbar plexus, which probably accounts for the escape area extending down only as low as the L.2 dermatomes. It was also discovered that on the left side a portion of the 1st lumbar paravertebral ganglion had been left behind

at operation and that, therefore, persistence of this ganglion would account for the asymmetry between the upper levels of the escape areas on the two sides.

CASE W.P. In this case resection of T.4–L.3 ganglia on each side was intended. The upper level of the anhidrotic area appears quite symmetrical, but has extended even higher to the T.3 dermatomes. The upper level of the escape area, however, is markedly asymmetrical. On the left side it extends into the T.12 dermatome, but on the right side it has reached much higher to at least the T.10 dermatome. There are two small 'islands' of sweating over the back of the anhidrotic area. The lower level of the escape area extends well down on the inner side of the legs to the L.3 dermatomes, even extending farther on the right side. No plethysmographic records were obtained on this patient.

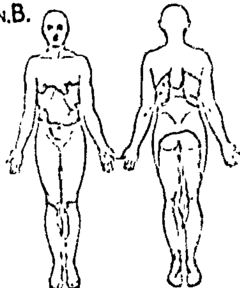
In none of these six cases is particular attention paid to sweating in the perineum, although in Case A.T. it is apparent that the escape area extends to the perineum, and in Case B.S. it is rather more evident than in the other cases. The significance of sweating in the perineum was not appreciated in the earliest cases, but is considered more fully later.

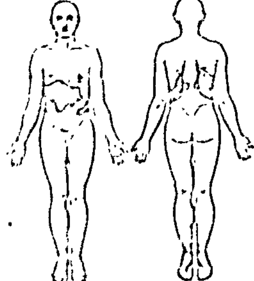
CASE MN.B. Fig. 5 shows a typical case, which also underwent carbachol testing, and was followed up for 2½ years. The resection on each side extended from T.5–L.3, and the first test was performed 2 months after the operation on the left side and 5½ months after that on the right. Subsequently, both thermoregulatory and carbachol testing were repeated at intervals of a year. The upper level of the anhidrotic area conforms with the intended levels of resection and therefore reaches the T.5 dermatome on each side, which just includes the nipples. The upper level of the escape area, however, is not so symmetrical, reaching T.11 on the left side, and to the rather higher level of T.10 on the right. The lower level of the escape area extends well down on the inner sides of the legs into L.3 dermatome.

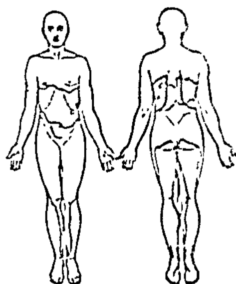
Carbachol testing, at the same time, showed sweating throughout the whole of the lumbar and sacral dermatomes. It is evident that the chains of 'islands' of sweating on the left thorax now coalesce into a band on this side, between the escape area and the normally innervated area in the upper part of the thorax. Also there is a similar band in the mid-line of the back. The [illegible] smaller after carbachol [illegible] been left behind *in situ* [illegible] but have lost their preganglionic supply from the cord. On each testing it will be evident that sweating has been retained in the perineum corresponding approximately to the S.4 and S.5 dermatomes.

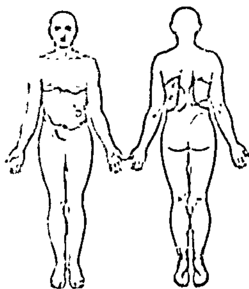
On testing again one year later, it will be seen that the general pattern of thermoregulatory sweating is essentially similar to that of the first observation, except perhaps that the lower level of the escape area on the back is now continuous with the area of perineal sweating in the natal cleft.

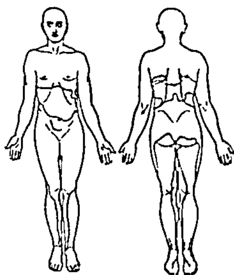
Carbachol sweating on this occasion has again extended over all the lumbar and sacral dermatomes, but the band of sweating on the left side of the thorax is again segmented into 'islands'. This is probably due to the fact that











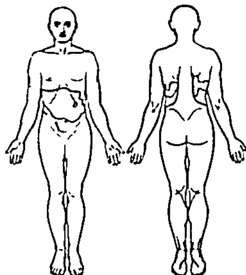


Fig. 5. Case Mn.B.

scar tissue has involved the postganglionic neurones or that the ganglion cells have died.

After 2½ years the general pattern is relatively unchanged, except that after thermoregulatory testing there now appears to be a continuous band on the left side of the anhidrotic area of the thorax and that the same pattern is constant when tested by carbachol. After the latter test, however, the midline of the back now shows continuous sweating. The upper level of the anhidrotic area of thermoregulatory sweating shows an extension downwards of about one dermatome. Possibly this may be due to the re-innervation of the anhidrotic area from the intact ganglion cells in the 4th thoracic ganglion on both sides.

The general observation should be made that, whereas variations may occur in the area of anhidrosis on the thorax, the area of anhidrosis in the lower lumbar and upper sacral dermatomes remains quite constant. This is the general rule found in almost all cases.

Plethysmography on the great toes was performed at the same time as the last testing. After heating the patient there was no change in the pulse wave and even a slight decrease in the blood flow. There was therefore no evidence of recovery of function of the vasomotor supply.

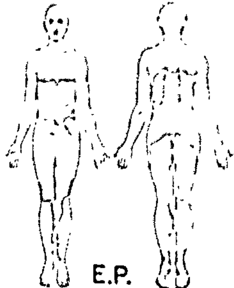
Fig. 6 shows the observations of two other cases who were tested with carbachol and were followed up on two occasions.

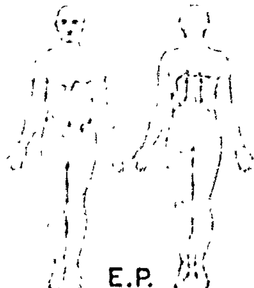
CASE E.P. This patient had a resection T.4–L.3 ganglia on each side. On first examination it is apparent that the upper level of the anhidrotic area is symmetrical in front and extends up to the T.5 dermatomes. From behind it appears to be not quite so symmetrical and extends rather lower on the left side. The upper level of the escape area is markedly asymmetrical—on the left side it is about the level of the L.1 dermatome, but there is a 'peninsula' of sweating extending along the line of an intercostal nerve (T.9?). On the right side the escape area extends upwards to the T.10 dermatome. The lower levels are relatively symmetrical and extend below the knee into the L.3 dermatome.

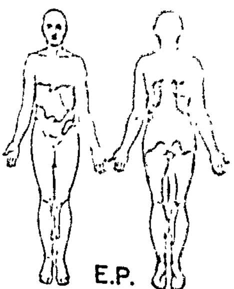
After carbachol sweating it is apparent that the belt, on the left side at about the T.9 dermatome has now widened, indicating that some ganglion cells in this region had retained intact their postganglionic nerve fibres, although they had been deprived of their preganglionic connections.

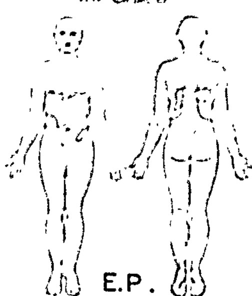
As in the previous case carbachol sweating is now apparent in the lower lumbar and upper sacral dermatomes.

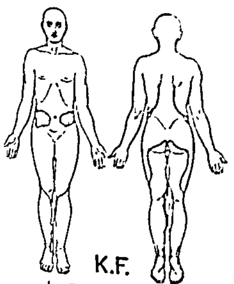
On testing again after an interval of two years, it will be seen that the anhidrotic area on the thorax is now slightly smaller than on previous occasions and that bands of sweating now appear on the back. The band of sweating along the line of the 9th intercostal nerve has now widened and is very similar to that observed on carbachol testing on the first occasion. In other respects the pattern after carbachol testing fits in closely with the thermoregulatory pattern. There is a slight extension downwards from the normally innervated area on the thorax into the anhidrotic area, and again from the escape area into the buttock and perineum in the natal cleft.











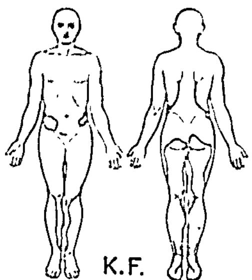


FIG. 6. Cases E.P., K.F.

Plethysmography on the toes carried out on the last occasion, showed that after reflex heating there was slight increase in the blood flow on the left side but not on the right. This slight evidence of recovery of vasomotor control on the left side is not supported by the sweating pattern.

CASE K.F. This patient had only a low level resection—from T.11–L.3 on each side. The patterns of anhidrosis, however, are quite symmetrical, the upper level of the anhidrotic area seems to extend rather higher to T.10 dermatomes, but there is a belt in the mid-line front and back. The upper level of the escape area is similarly symmetrical extending to L.1 dermatomes on each side, but the lower level extends well down into the L.3 dermatome on the right and not quite so low on the left. Carbachol testing was done on the same occasion, two weeks after the operation on the left side, and showed the same area of anhidrosis on the thorax as after thermoregulatory sweating. After carbachol, however, sweating appeared in the lower lumbar and upper sacral dermatomes as was to be expected. There was, however, only faint sweating on the soles of the feet and lower legs, as the skin here was very dry and scaly.

On testing again a year later, the patterns were almost unchanged, except that after both thermoregulatory and carbachol sweat-testing, the anhidrotic area on the thorax (or rather abdomen) is now slightly smaller than on the first occasion. The anhidrotic area on the legs is almost unchanged and again showed sweating on carbachol testing.

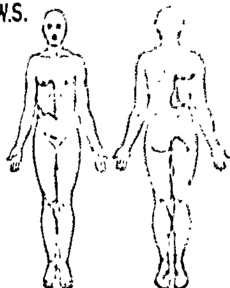
This was one of the earlier cases and no plethysmographic observations were made.

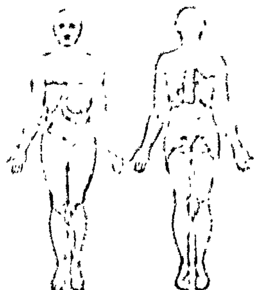
Figs. 7, 8 and 9 show the patterns obtained on three cases which were followed up regularly for three years or more.

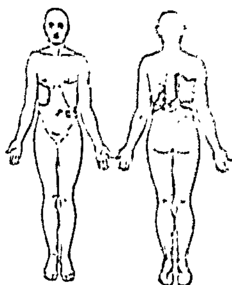
CASE W.S. This case had a resection of the paravertebral chain from T.4–L.2 on the right and later T.10–L.3 on the left. He was first tested two weeks after the first operation. The pattern of anhidrosis was as to be expected, and showed the upper level of the anhidrotic area at T.4 and the upper level of the escape area at about T.11. The lower level of the escape area extended below the knee to L.3. On the thorax the pattern is limited to the mid-line, though it does not reach quite so far, over the mid-dorsal spines (see also Case J.T.—Fig. 9).

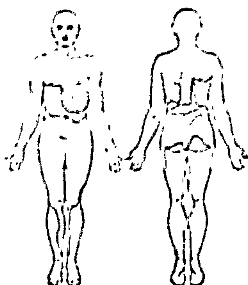
Two months later he was tested again both for thermoregulatory and carbachol sweating. It will be noticed that the pattern on the right side is essentially similar to that noted earlier, except that there is some irregularity at the upper level of the escape area, and also a patch below the anterior superior iliac spine on this side. On the left side the operation had been [illegible]

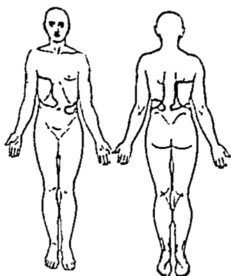
tends farther down the inner side of the leg well into L.3 dermatome. The escape area still extends into the perineal sweating area in the natal cleft. On carbachol testing the area of anhidrosis on the thorax is rather smaller on the right side and does not reach the mid-line in front, but on the left side the band of anhidrosis is broken up into small 'islands'. As is usual, sweating on


W.S.
L. NORMAL.
R T4 - L2 2 Weeks


L T10 - L3 3 Weeks
R T4 - L2 10 Weeks


L. T10 - L3. 4 Weeks
R. T4 - L2. 11 Weeks
After Carbachol.


L. T10 - L3 17 Months
R T4 - L2 18¾ Months


L. T10 - L3 17 Months
R. T4 - L2 18¾ Months
After Carbachol

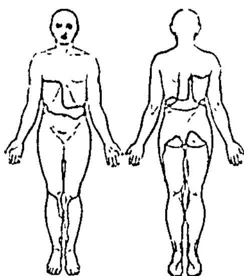

L. T10 - L3 40 Months
R. T4 - L2 41¾ Months

Fig. 7. Case W.S.

testing with carbachol appears in the lower lumbar and upper sacral dermatomes.

On further testing 18 months later, it will be seen that the pattern for thermoregulatory sweating is almost identical with that obtained earlier, except that the patch of anhidrosis below the anterior superior iliac spine has now disappeared. There is also some extension downwards of the normal sweating area on the thorax into the upper level of the anhidrotic area.

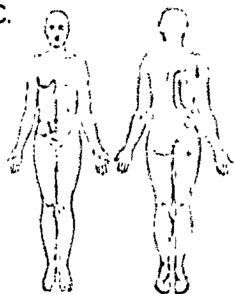
Carbachol sweating at this time shows that on the right side the pattern remains very similar to that observed earlier, but that on the left side the scattered 'islands' have now coalesced into an incomplete belt. This is probably due to involvement of the ganglion cells or their fibres in scar tissue.

A third thermoregulatory sweating test was performed 3½ years after operation. The over-all pattern is almost identical with that found before. There is, however, a continuous band of sweating in the left axillary line across the belt of anhidrosis. This indicates that there has been some recovery of function of both pre- and postganglionic neurones (mostly preganglionic neurones) in this area affecting apparently the T.10 and T.11 dermatomes. The anhidrosis in the L.4–S.2 dermatomes remains unchanged on each side. Carbachol sweating test was not performed on this occasion.

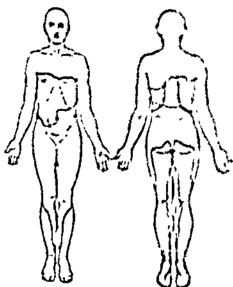
Reflex plethysmography on the toes, however, shows a slight increase of the pulse wave on the left side, and slight increase of the blood flow on the right, after heating the patient. There is thus some evidence of recovery of vasomotor control, which is not borne out by the sweating pattern at this level.

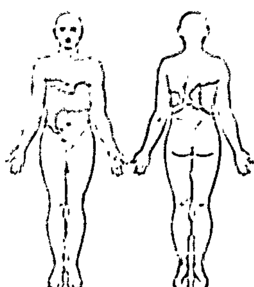
This patient is of particular interest in regard to the occurrence of sterility after thoraco-lumbar ganglionectomy. At the time of the second testing nineteen months after the first operation, the patient stated that he thought he was producing semen on intercourse, but, though he experienced orgasm, this was not accompanied by rhythmic ejaculation. His child was born sixteen months later. A.B.O. blood grouping of the child is not incompatible. The evidence of the recovery of sympathetic function to the pelvic viscera seems to be consistent with that of the return of function of autonomic supply to the skin in a small area of the T.10 and T.11 dermatome on the left side (see Northfield and Monro, 1953).

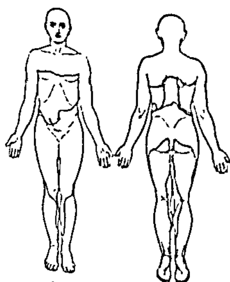
This patient was the first upon whom the carbachol sweating test was performed. At that time the sweating produced by carbachol, in the lower lumbar and sacral segments, was demonstrated both by the increase in the electrical skin resistance and also by the application of the dye quinizarin which changes to a deep-blue colour in contact with sweat. It was found that the sweat glands in this area, which was anhidrotic to thermoregulatory testing, was strongly marked as little blue specks at the mouths of the sweat pores. Photographs were made on this occasion. The area of sweating, as demonstrated by quinizarin, fitted closely into the patterns obtained by the electrical method except that the latter extended about one centimetre farther and was therefore more sensitive.


L.C.
L NORMAL
R




L. T4 - L3 12 Months
R. T5 - L3 13½ Months


L. T4 - L3. 12 Months
R T5 - L3 13½ Months
After Carbachol


L T4 - L3 35 Months
R T5 - L3 36½ Months

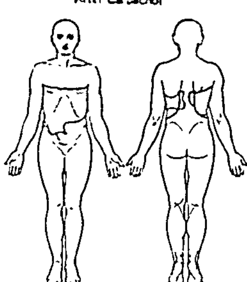

L T4 - L3 35 Months
R. T5 - L3 36½ Months
After Carbachol

Fig. 8. Case L.C.

CASE L.C. (Fig. 8). This patient had a resection of paravertebral ganglia intended T.5–L.3 on the right side, and was examined one month later. It will be apparent, however, that the upper level of the anhidrotic area on this side has extended well up into the T.4 dermatome, and that the upper level of the escape area is that of L.1 dermatome. The lower level of the escape area extends well down below the knee into L.3 dermatome. Both on front and back it is limited to the mid-line, except on the lower part of the back, where it does not reach quite so far over the lower lumbar vertebrae. Subsequently the T.4–L.3 ganglia were resected on the left and the patient tested again. It will be observed that there is very close correspondence between the anhidrotic area on the right side on the front, though on the back the area over the hip and the area below the curve of the incision, where it had not reached the mid-line on first testing, do not extend as far as before. On the left side, the upper level of the anhidrotic area is symmetrical with the right in front, reaching T.4 dermatome; but behind, it does not seem to be quite as high. The upper level of the escape area, however, is much higher on the left than on the right and reaches the T.10 dermatome. Behind, it is approximately symmetrical with the new level on the right side. This would suggest that preganglionic fibres have re-established functional connections with ganglion cells left in this area. Possibly these ganglion cells are in intermediate ganglia in the lower thoracic nerve roots, or in a portion of the paravertebral chain on this side, which was omitted from resection as it passed through the diaphragm. The escape area is continuous with the area of sweating on the perineum in the natal cleft.

The patient was examined again after a year, and the thermoregulatory pattern was found to be almost identical and unchanged from that observed earlier. There is, perhaps, a slight extension downwards of the normally innervated area into the right side of the upper level of the anhidrotic area above the scar of the incision. There is also slight widening of the sweating in the perineum in the natal cleft.

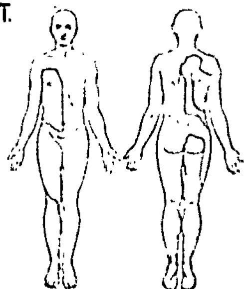
Carbachol sweating at this time shows two patches of encroachment into that of thermoregulatory sweating—on the front over the xiphisternum, and on the right side around the umbilicus. On the back also, sweating appears near the mid-line on the left side, except for a small 'island'. As usual, sweating is apparent in the lower lumbar and upper sacral dermatomes.

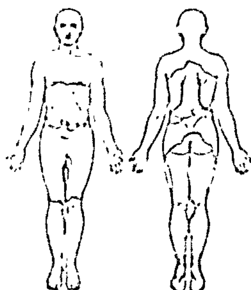
When examined three years after operation, the pattern of thermoregulatory sweating still remains unchanged, but on carbachol sweat-testing, at this time, the gap over the mid-line at the back has become more definite. The patch over the xiphisternum has disappeared. Plethysmography on this patient showed no change in blood flow or pulse wave in the toes after heating.

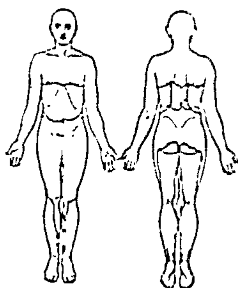
CASE J.T. (Fig. 9). This patient had a resection T.5–L.3 on both sides and was examined eleven days after first operation (on right side). It will be observed that the upper level of the anhidrotic area extends well up to the second intercostal space in front, and probably the same level or a little higher behind. Also that it extends across to the left of the mid-line at about the level of the 3rd and 4th thoracic spines.

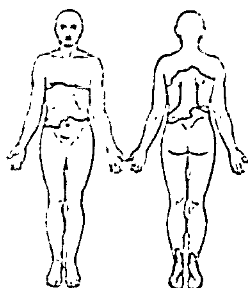
In this case it was quite definite that the area of anhidrosis at these approximate levels T.3 and T.4 had extended across the mid-line onto

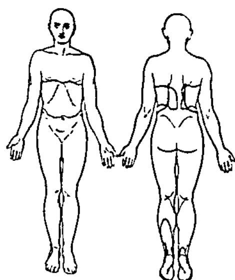
J.T.











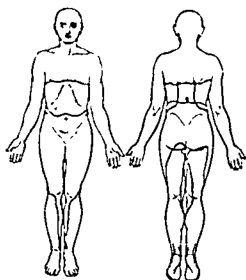


Fig. 9. Case J.T.

the right side for about 1½ inches (4 cm.). This was the only case in which it was noted, but many cases were not tested when only one operation had been performed. It should be recalled that in Case W.S. after operation on the right side only, anhidrosis was not present for about 1 inch (2·5 cm.) on the right side of the mid-line at the levels of the mid-thoracic spines. It seems probable that in these two cases (and possibly also in Cases M.A.B. and K.F.) part of the dermatome is not supplied by the posterior primary division at that level but receives instead a supply from the opposite side. This aspect was not considered by Foerster (1933), since most of his operation cases had undergone a laminectomy and it was impossible to examine an area so close to the mid-line. Sherrington (1893) found that the overlap of dermatomes was greater in the mid-ventral rather than the mid-dorsal line, where it was never greater than 1 cm. in a small monkey. Head does not appear to consider this question of overlap across the mid-line.

In the observations reported here it seems hardly possible for the operation on the left side of Case J.T. to have involved injury to sweating pathways via thoracic nerves on the right side: it must be concluded that in certain individuals an autonomic dermatome may extend slightly across the mid-line.

When examined again two months later, which was two weeks after the operation performed at the same levels on the left side, it will be noted that the upper level of the anhidrotic area is symmetrical and reaches into T.5 dermatome, which is therefore two segments or so lower than it was on the right side at 11 days after operation. The upper level of the escape area is slightly irregular and there are a few scattered 'islands' of sweating above it on the left side, but on the whole it seems to follow the T.12 dermatome. The lower level of the escape area extends below the knees into L.3 dermatome. On this occasion the area of sweating in the perineum was not continuous with that of the escape area.

On carbachol testing on the same occasion, the pattern of anhidrosis on the thorax is almost unchanged except where the 'islands' above the escape area on the left side are now found to be sweating.

The usual carbachol sweating in the lower lumbar and upper sacral dermatomes was not entirely evident. The soles of the feet and the skin over the tendo Achillis were very dry and scaly. It is probably for this reason that no sweating could be detected here, even though the postganglionic connections to the sweat glands may still have been functional.

When the patient was tested again, almost two years after operation, it will be seen that the anhidrotic area is now more symmetrical. The upper level remains unchanged. But the upper level of the escape area has encroached upwards about one segment to T.11 dermatome on each side. The lower level of the escape area has extended slightly on the inner side of the calf and is patchy hereabouts—small islands of sweating being detected.

The sweating in the natal cleft from the perineum is now continuous with the escape area. On the back it will be noticed that in the mid-line of the anhidrotic area there are two encroachments on the upper and lower edges, and also a small 'island' of sweating.

Carbachol sweat-testing, at the same time, shows that the anhidrotic area is almost unchanged, except on the mid-line at the back, where these extensions of thermoregulatory sweating are now continuous. The soles and the back of the left calf had remained very dry and scaly, and showed no apparent sweating to carbachol.

When the patient was tested a third time, three years after operation, the thermoregulatory sweating pattern was almost identical with that obtained at two years. There was, however, slight extension of the normal intact area downwards onto the upper edge of the anhidrotic area on the left side of the back, and also on the buttock, particularly on the right side where it has become more obviously continuous with the sweating in the perineum.

Plethysmography on the toes carried out on this occasion showed no change in blood flow or pulse wave on heating the patient.

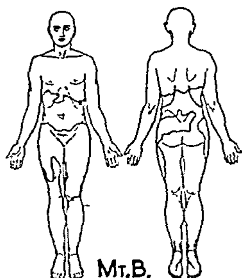
Fig. 10 shows the observations obtained on three cases who had rather unusual sweating patterns when first examined shortly after operation, and who showed rather more recovery than usual when re-examined later.

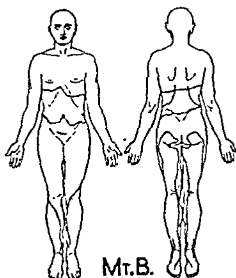
CASE MR.B. The patient had a resection T.9–L.2 on left side and T.7–L.3 on the right. The upper level of the anhidrotic area is very irregular, but reaches about T.9 on the left and T.8 on the right. There is also a patch of sweating around the umbilicus. The upper level of the escape area is more symmetrical at about L.1 dermatomes, but the anhidrotic area is continuous across the escape area over the right buttock with the area of anhidrosis in the upper sacral dermatome. The lower level of the escape area is markedly asymmetrical and the right side, which was examined only two weeks after operation, shows only an irregular patch on the front of the thigh. On the left side it extends down to the inside of the knee.

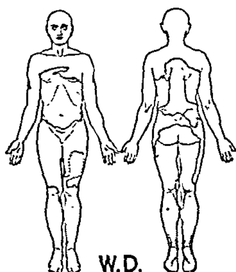
When examined again after an interval of three years the general pattern is more symmetrical and the dermatome levels are relatively the same except that the lower level of the escape area has now extended well down both legs on the inner sides into L.3 dermatomes. Also on the back, it extends into the area of sweating in the perineum, in the natal cleft, and in the fold of the buttocks.

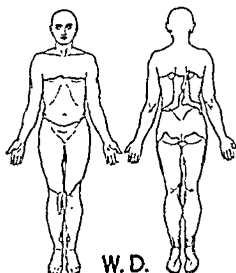
Plethysmographic observations performed on the toes, on the later occasion, showed a slight increase in blood flow and pulse wave on heating the patient. There is therefore some evidence of recovery of vasomotor tone which is not entirely borne out by the sweating patterns.

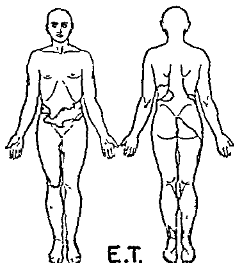
CASE W.D. The intended level of resection was T.4–L.3 on both sides. On the left side the upper level of the anhidrotic area has reached this dermatome, but on the right, which was examined two weeks after operation, it seems to have extended to a higher level—possibly to T.2. The upper level of the escape area in front is relatively symmetrical at L.1 dermatome, but again on the right buttock a 'peninsula' of anhidrosis extends towards the upper sacral anhidrotic area. The lower level of the escape area extends only in a











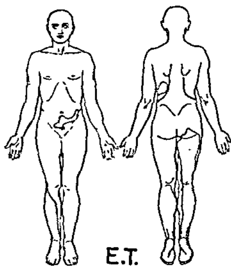


Fig. 10. Cases Mt.B., W.D., E.T.

patchy indefinite position on the left thigh - not encroaching beyond the L.2 dermatome, but on the right side extends below the knee into L.3 dermatome.

On re-examination after nearly three years the anhidrotic area is more symmetrical in front, now reaching T.4 dermatomes on each side, but behind, in the mid-line over the spine, there is a continuous band of sweating extending down into the escape area. The lower level of the escape area has now extended down to the level of the knee on the left side and a little farther on the right, with two small 'islands' of sweating over the shins. Behind, it has encroached down over both buttocks and is now continuous with the sweating of the perineum in the natal cleft.

Plethysmographic observations on the later occasion showed no change in the blood flow or pulse wave on heating the patient.

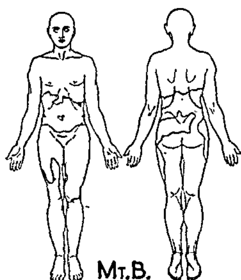
CASE E.T. Resection was T.7-L.3 on the left and T.9-L.2 on the right. Evidence from the position of clips on X-ray examination served to confirm this intended level of resection, but it is apparent that the sweating pattern is very unusual. On the left side the upper level of the anhidrotic area reaches T.9 dermatome, and it is slightly lower on the right, but very irregular, at approximately T.10. On the back there is a continuous band of sweating across the anhidrotic area and joining the escape area, especially on the right. The lower level of the escape area, on the left, appears to extend almost onto the whole of the leg except for the sole of the foot. On the right it reaches only to the level of the knee at the L.2 dermatome. On re-examination one year later, it is evident that the anhidrotic area on the right had disappeared, and on the left had become much reduced in size and now consists only of about the T.12 dermatome. The whole of the left leg is sweating, however, and the escape area has extended down to the inner side of the right leg as far as the medial malleolus.

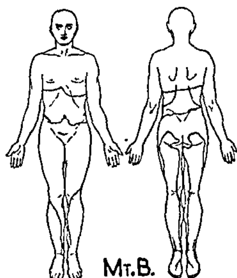
Although at first this might be regarded as marked recovery of function, it seems more probable that this most unusual pattern is really due to imperfect resection, especially on the left side (or possibly due to the presence of a double paravertebral lumbar chain). No plethysmographic observations were made on this patient.

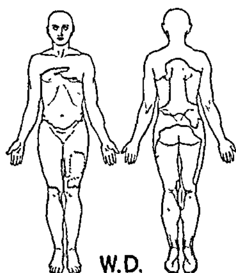
It was not possible to follow up this patient later as she died from the effects of hypertension. Although a post-mortem examination was performed, no notes were made of the appearance of the sympathetic chain and the author did not learn of her death until too late.

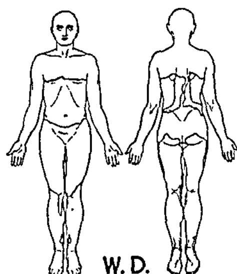
Fig. 11 shows the observations obtained on two patients who had extension of the anhidrotic area into the arm when examined shortly after thoraco-lumbar sympathectomy.

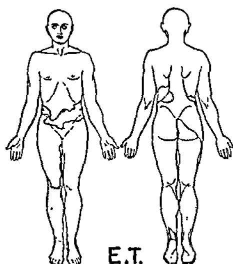
CASE P.F. The intended levels of resection on each side were T.4-L.3. Two weeks after the first operation (on the right side), the upper level of the anhidrotic area was found to extend well up to T.2. dermatome in the axilla and under part of the upper arm down to the level of the elbow. This corresponds closely with the T.2 dermatome according to Foerster, and might therefore be considered to be extending above this level. There is also a small patch of anhidrosis above the right anterior iliac spine, which is similar to











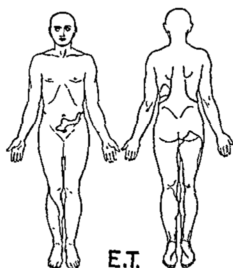


Fig. 10. Cases Mt.B., W.D., E.T.

patchy indefinite position on the left thigh—not encroaching beyond the L.2 dermatome, but on the right side extends below the knee into L.3 dermatome.

On re-examination after nearly three years the anhidrotic area is more symmetrical in front, now reaching T.4 dermatomes on each side, but behind, in the mid-line over the spine, there is a continuous band of sweating extending down into the escape area. The lower level of the escape area has now extended down to the level of the knee on the left side and a little farther on the right, with two small 'islands' of sweating over the shins. Behind, it has encroached down over both buttocks and is now continuous with the sweating of the perineum in the natal cleft.

Plethysmographic observations on the later occasion showed no change in the blood flow or pulse wave on heating the patient.

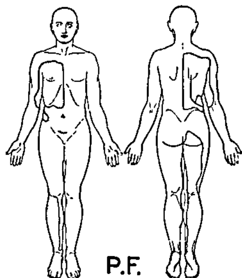
CASE E.T. Resection was T.7–L.3 on the left and T.9–L.2 on the right. Evidence from the position of clips on X-ray examination served to confirm this intended level of resection, but it is apparent that the sweating pattern is very unusual. On the left side the upper level of the anhidrotic area reaches T.9 dermatome, and it is slightly lower on the right, but very irregular, at approximately T.10. On the back there is a continuous band of sweating across the anhidrotic area and joining the escape area, especially on the right. The lower level of the escape area, on the left, appears to extend almost onto the whole of the leg except for the sole of the foot. On the right it reaches only to the level of the knee at the L.2 dermatome. On re-examination one year later, it is evident that the anhidrotic area on the right had disappeared, and on the left had become much reduced in size and now consists only of about the T.12 dermatome. The whole of the left leg is sweating, however, and the escape area has extended down to the inner side of the right leg as far as the medial malleolus.

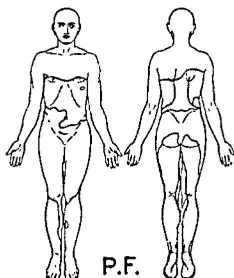
Although at first this might be regarded as marked recovery of function, it seems more probable that this most unusual pattern is really due to imperfect resection, especially on the left side (or possibly due to the presence of a double paravertebral lumbar chain). No plethysmographic observations were made on this patient.

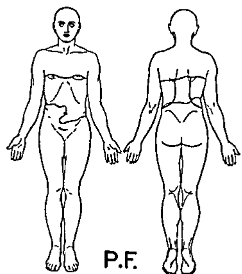
It was not possible to follow up this patient later as she died from the effects of hypertension. Although a post-mortem examination was performed, no notes were made of the appearance of the sympathetic chain and the author did not learn of her death until too late.

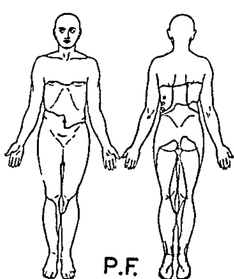
Fig. 11 shows the observations obtained on two patients who had extension of the anhidrotic area into the arm when examined shortly after thoraco-lumbar sympathectomy.

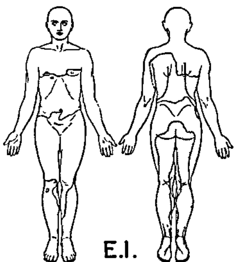
CASE P.P. The intended levels of resection on each side were T.4–L.3. Two weeks after the first operation (on the right side), the upper level of the anhidrotic area was found to extend well up to T.2. dermatome in the axilla and under part of the upper arm down to the level of the elbow. This corresponds closely with the T.2 dermatome according to Foerster, and might therefore be considered to be extending above this level. There is also a small patch of anhidrosis above the right anterior iliac spine, which is similar to











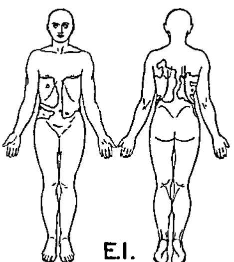


FIG. 11. Cases P.F., E.I.

that observed in one or two other cases. It never persisted for long, and is probably due to section of a branch of the ilio-hypogastric nerve in the lower end of the wound incision. On testing again 4½ months after operation on the right side and 2½ months after that on the left, the upper level of the anhidrotic area is now relatively symmetrical in front in the T.4 dermatome, although behind it reaches rather a higher level. The upper level of the escape area reaches only the L.1 dermatome on the left, but on the right extends higher to T.10, which is approximately the same level as before. The lower level of the escape area extends down below the knees into L.3 dermatomes on each side.

Carbachol sweat-testing on this occasion shows the anhidrotic area relatively unchanged except for a slight encroachment upwards from the escape area above the right buttock. Sweating is found as usual in the lower lumbar and upper sacral dermatomes.

On testing again almost two years after operation, the pattern of thermoregulatory sweating is almost unchanged except that a few 'islands' of sweating now appear on the left side of the thorax on the back, and that the escape area has extended upwards in a similar pattern as found after carbachol sweating shortly after operation.

This would seem to suggest that ganglion cells had been left intact in this region and that they had now re-established connection with preganglionic fibres. The escape area was continuous with the area of sweating on the perineum in the natal cleft on both occasions but has now become more extensive. Plethysmographic observations on the great toes showed no change in blood flow or pulse wave after heating the patient.

NOTE ON PILO-ERECTION. This patient showed a pilo-erection response of so-called dermatographia. On stroking anywhere on the body, at first each line of hairs was erected in a 'gooseflesh' response, and later this area became reddened and there was a suggestion of a slight wheal. It was noted on this patient and also in others (though not so markedly) that this dermatographic pilo-erector response could be elicited even in the area of anhidrosis on the thorax, which is the same area as had shown complete anhidrosis after carbachol and was therefore presumed to have been deprived of its postganglionic supply.

On stroking the skin with a pointer, a 15-mm.-wide patch of local pilo-erection appeared within two to three seconds, both in the sympathectomized area and the non-sympathectomized area. This lasted about ten seconds and persisted longer in the latter area. The area of pilo-erection was then replaced by a red flare response lasting about a minute and maximal in about thirty seconds. At the first observation shortly after operation, it was noticed that sensation was diminished in the curves of the wound incisions—probably due to trauma to the intercostal nerves although there was nowhere complete analgesia. It was very evident that the pilo-erector response could be retained in all areas of skin except in this relatively analgesic area. Two years after operation when the patient was examined again, the pilo-erector response could

now be obtained in the curves of the wound incisions, where it had been absent on the first occasion. Full sensation had returned to this area by this time.

These observations seem to throw some doubt on the claim that the pilo-erector mechanism is an autonomic response mediated through the paravertebral sympathetic chain from the thoraco-lumbar outflow of the sympathetic. It would seem that the mechanism is more dependent on the integrity of the posterior root innervation rather than that of the autonomic sympathetic. The general explanation of dermatographia is thought to be due to the local production of histamine. Why should not, therefore, histamine be produced in the skin of the curve of the wound incision?

Similar observation has been made by Brodal (1948—*page 372*), though he believes that this local response is mediated only by reflexes passing only at the levels of the sympathetic outflow. No other account seems to be available in the literature. Brown and Adson (1929) had reported that local pilomotor reflexes persisted on the shoulder where the skin was anhidrotic after cervico-dorsal ganglionectomy, but post-ganglionic innervation was probably intact here in their cases. Fig. 12*a*, *b*, *c* and *d* show four photographs taken at intervals of a few seconds after stroking the skin of this patient. These photographs are prepared from originals in colour. On other patients who showed this phenomenon, the timing of appearance of the different reactions was essentially similar, but they were not quite so evident and could not therefore be so well demonstrated as in these photographs.

CASE E.I. This case had a resection T.4–L.3 on both sides, but two weeks after the operation, on the left side it was found that the upper level of the anhidrotic area extended well up into T.2 dermatome and into the axilla and underside of the arm approximately to the level of the upper half of the humerus. On the right side the upper level of anhidrotic area reached T.4 dermatome. The upper levels of the escape area, although not quite symmetrical, reached about L.1 dermatome, and the lower level extends below the knees into L.3 dermatomes. When carbachol sweat-testing was performed a week later, it was found that in the mid-line, both front and back, sweating appeared in the band across the anhidrotic area and also on the left side in the T.10 dermatome. This encroachment in the mid-line occurs in some other patients on carbachol sweating, and it would seem to suggest the possibility that there are ganglion cells which supply this area, but more peripherally situated, and which are ordinarily severed of their preganglionic connections by the paravertebral sympathectomy. Presumably also some ganglion cells remained on the left side, particularly in the T.10 dermatome. The lower lumbar and upper sacral dermatomes sweat as usual to carbachol. No plethysmographic observations were obtained on this patient.

Fig. 13 shows two more cases who had been tested both by heating and with carbachol.

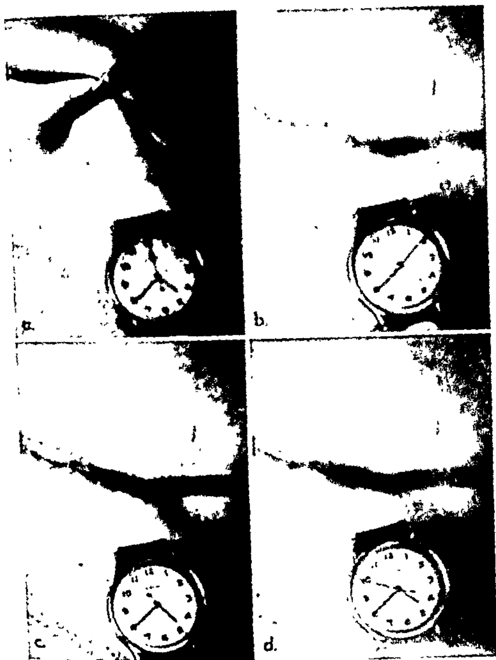


FIG. 12. Pilo-erector response to stroking (Case P.T.). Sympathectomized area above line, 'escape' area below line. Right wound incision at lower edge.

a. Stroking with blunt pencil
b. Band of pilo-erection
c. Flare appearing
d. Pilo-erection passed off; flare only present

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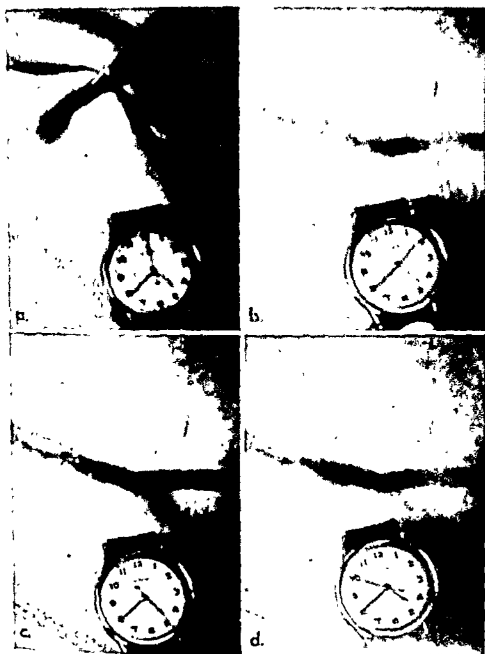
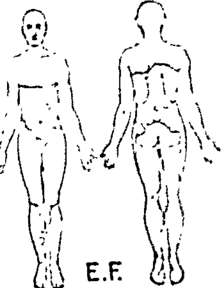
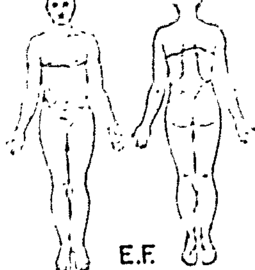
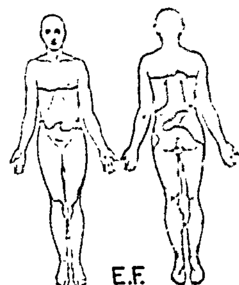


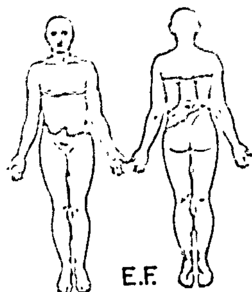
Fig. 12. Pilo-erector response to stroking (Case P.F.). Sympathectomized area above line, 'escape' area below line. Right wound incision at lower edge.

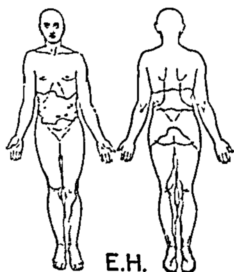
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b. Band of pilo-erection
c. Flare appearing
d. Pilo-erection passed off; flare only present











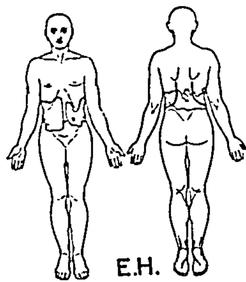


Fig. 13. Cases E.F., E.H.

CASE E.F. The intended levels of resection were T.5–L.3 on the left and T.4–L.3 on the right. The upper level of the anhidrotic area appears quite symmetrical in T.5 dermatomes on each side. The upper level of the escape area is at about L.1 dermatome on the left, but reaches to T.12 on the right, and the level of anhidrosis extends in a band across the left buttock to the upper sacral dermatomes. The lower level of the escape area extends below the knees into L.3 dermatomes on each side. The area of sweating in the perineum is not continuous with that of the escape area. On carbachol sweat-testing, the level of the anhidrotic area is relatively unchanged, except that the band connecting the anhidrotic area with the sacral anhidrotic area has now disappeared and a small 'island' of sweating is apparent on the right lower abdomen.

On testing again a year and a half after operation, the pattern of thermoregulatory sweating is almost unchanged—and the band on the left buttock persists as before, nor does the escape area connect with the sweating in the perineum. Carbachol sweat-testing on the same occasion showed a very similar pattern as it did before, except that a small area of sweating has appeared on the mid-line of the back over the lower thoracic spines.

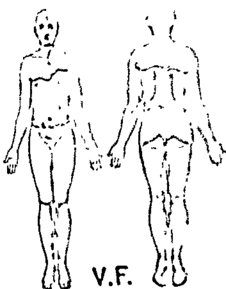
CASE E.H. These patterns were obtained after resection T.8–L.3 on the left and T.7–L.3 on the right. The upper level of the anhidrotic area on each side reaches T.7 dermatome, but the upper level of the escape area is not so symmetrical—reaching L.1 on the left and T.12 on the right. The lower level of the escape area extends well down into L.3 dermatomes on both sides.

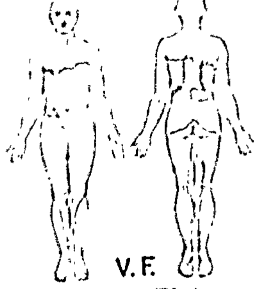
On carbachol testing this patient one week later, it will be observed that the pattern of the anhidrotic area on the thorax lies relatively within the pattern for thermoregulatory testing, but that some of the 'islands' in the former had now coalesced and also that a band of sweating is present in the mid-line across the anhidrotic area. On the back there is also an extension over the lower thoracic spines but it is not complete. In many respects, however, the occurrence of carbachol sweating in the mid-line front and back is very similar to that noted in Case E.I. (Fig. 11). As usual the lower lumbar and upper sacral dermatomes show sweating to the drug.

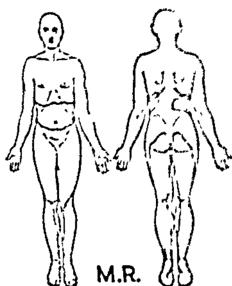
No plethysmographic observations were made in this case.

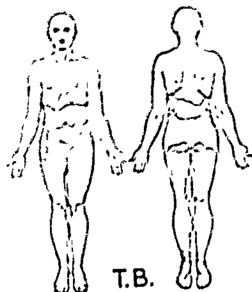
Fig. 14 shows the results in one case of high retro-pleural resection compared with four cases of transthoracic thoraco-lumbar sympathectomy.

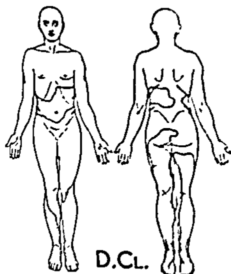
CASE V.F. On the left side the resection was carried as high as the T.2 ganglion, whereas on the right it was as high as T.4 ganglion. In both cases it was carried down to the L.3 ganglion. The case was first tested about five weeks after the operation on the right side (not illustrated), and showed a pattern on that side very similar to that obtained twelve months later. On the left side, at 12 months, it is evident that the high level of the anhidrotic area has persisted and is about a segment or two higher than that on the right side—reaching T.2 on the left and T.3 on the right. The upper level of the escape area is relatively segmental, extending approximately to T.12 dermatome on each side or slightly lower. The lower level of the escape area extends below the insides of the knees on both sides into L.3 dermatomes.

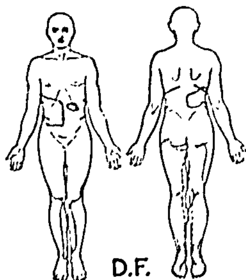












V.F., retro-pleural. Cases M.R., T.B., D.Cl., D.F., transthoracic.

This case is unusual, however, in that no sweating was evident to the eye, twelve months after operation, on the left arm or left side of the head and neck in the area lying above the dotted line, but in this area it could still be detected by the electrical skin resistance meter. There was a band of free sweating above the anhidrotic area extending into the axilla approximately in the T.1 and T.2 dermatomes. It is therefore evident that the majority of preganglionic fibres to the left upper limb had left the spinal cord below the third thoracic ganglion. This is the only case which has shown a persistently high level of anhidrosis in this area, though in one case examined by the author recently, similar relative anhidrosis had been found on the hand by direct observation, but a line of demarcation could not be found with the electrical skin resistance meter.

Carbachol sweating on the same occasion (not illustrated) showed that the area of anhidrosis on the thorax corresponded almost exactly to that of thermoregulatory sweating. The area on the left arm sweated almost as freely as on the right. As usual, sweating appeared on the lower lumbar and sacral dermatomes.

On testing again seventeen months after operation the pattern of thermoregulatory sweating is almost unchanged from that of the earlier observations, except that there has now appeared a band of sweating over the spine rather to the right of the mid-line in the upper part, and to the left of the mid-line in its lower part where it connects with the escape area. The sweating on the two arms appeared to be equal at this stage, so presumably new preganglionic fibres had established synapses with the ganglion cells to the left arm. The area of sweating in the perineum, which was at first continuous with that of the escape area, seemed to be separated by a small band of anhidrosis at the base of the spine, at the second examination.

Plethysmographic observations on the toes showed unchanged pulse waves and slight reduction of blood flow after heating the patient, there is thus no evidence of vasomotor control having returned to the lower limbs.

CASE M.R. This patient had a transthoracic sympathectomy performed through double incisions on each side. The upper level of resection extended only to the T.6 ganglion, but the chain was followed down to the diaphragm. It was picked up again below the diaphragm, through the lower incision, and resected down to the L.3 ganglion. It will be noticed that the upper level of the anhidrotic area reaches about T.7 dermatome on each side, and the upper level of the escape area is almost symmetrical at about the T.12 dermatome, though perhaps a little lower on the right. On the back there is a large gap on the left side which includes certainly the whole of the posterior primary division of the nerve roots at this level. The lower level of the escape area on both sides extends well below the knees into the L.3 dermatomes. The area of sweating in the perineum is continuous with the escape area.

Plethysmography on the great toes was performed at the same time and showed some reduction in the blood flow on both sides, after the patient was heated, and also a corresponding reduction in the size of the pulse waves. (These measurements are not included in Part Three.)

This case is unusual, however, in that no sweating was evident to the eye, twelve months after operation, on the left arm or left side of the head and neck in the area lying above the dotted line, but in this area it could still be detected by the electrical skin resistance meter. There was a band of free sweating above the anhidrotic area extending into the axilla approximately in the T.1 and T.2 dermatomes. It is therefore evident that the majority of preganglionic fibres to the left upper limb had left the spinal cord below the third thoracic ganglion. This is the only case which has shown a persistently high level of anhidrosis in this area, though in one case examined by the author recently, similar relative anhidrosis had been found on the hand by direct observation, but a line of demarcation could not be found with the electrical skin resistance meter.

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CASE D.F. This case of transthoracic resection T.6–L.3 on each side again shows evidence of imperfect resection on the left side. The anhidrotic area on the right side reaches T.6 dermatome, and the upper level of the escape area on this side reaches T.12 dermatome. On the left side, however, the anhidrotic area is represented only by a small patch on the left costal margin on the front of the abdomen. The lower edges of the escape area are relatively indeterminate. On the front of the leg they appear to extend well down to the malleoli, but on the back it was difficult to demarcate an exact margin of anhidrosis though there was a change noted below the buttocks and on the inside of the legs. Again it was apparent that the operation must have been relatively incomplete, and especially so on the left side.

Plethysmographic observations on the great toes showed moderate increase of the blood flow and pulse wave on the left side, after heating the patient, and on the right side there was marked increase in blood flow and pulse wave. This indicated that a great deal of vasomotor supply had been retained, especially on the right side.

In these four cases of transthoracic paravertebral sympathectomy, there is evidence of imperfect resection either in sweating patterns or presence of vasomotor control or both. Most other cases which have been examined by the author more recently show similar incomplete patterns (six out of seven). It is hardly likely that they all had double sympathetic chains or other anatomical abnormality. It is not thought that this sweating can be due to regeneration, since the intervals are all relatively short, and similar cases with one exception (E.T., Fig. 10), which had been operated on by the retro-pleural approach, have all showed constant patterns which have persisted unchanged for much longer periods of time. It is probable that the retro-pleural operation is more complete, since all rami and ganglion cells are more easily removed in the separation forwards of the pleura from the chest wall. In the transthoracic operation, although the sympathetic chain may be resected in one piece, a portion of a ramus communicans must lie behind the pleura in close relation to blood vessels, and if there are any ganglion cells in this region they would persist and would be able to exert their autonomic control of the sweat glands and blood vessels.

There is one other case of thoraco-lumbar sympathectomy in this series. It was one of the earlier cases, and is particularly interesting as it furnished the key to the explanation of sweating in the escape areas. It will be discussed later in Chapter 7, when the occurrence of the intermediate ganglia in relation to the escape area is considered and their anatomy is described.

GENERAL CONCLUSIONS

After thoraco-lumbar sympathectomy, sweating activity is lost in all dermatomes below or next below the intended level of resection except in an escape area which comprises the L.1, L.2 and often L.3 derma-

tomes. It is frequently found that the escape area may include T.12 or T.11 dermatomes on one or both sides. In about one-third of all cases the L.3 dermatome tended to extend farther down the inner side of the leg than usual.

Sweating activity is also retained in the perineum corresponding to S.4 and S.5 dermatomes. This is discussed more fully in Chapter 10.

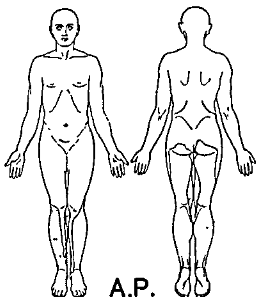
The greater facility of the transthoracic thoraco-lumbar sympathectomy has encouraged surgeons to perform this type of operation rather than the older and anatomically more sound retro-pleural approach. This is unfortunate, since it would appear that very few of these patients can have undergone adequate sympathectomy. The resulting early recovery of function may have done much to suggest to physicians that all forms of sympathectomy are of little use in hypertension. The bad results are really due to inadequate surgery. One of the few objective reports on patients operated on by this approach by other surgeons shows that sweating activity is often retained in areas where, after the more adequate retro-pleural operation, it would be expected to be absent (see Wilson, 1950).

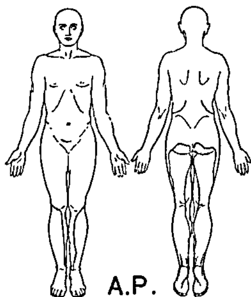
In the author's opinion a return to the more laborious but more permanent retro-pleural operation in selected cases would show consistently more successful cures. Also it is probably unnecessary to extend the operation much higher than, say, T.6; and even T.8—as originally suggested by Adson, Craig and Brown (1935)—may be quite satisfactory. It is probably more important to perform complete resection of the splanchnics and sympathetic chains as they pass through or behind the crura of the diaphragm and to continue the dissection to the level of the middle of the 3rd lumbar vertebra.

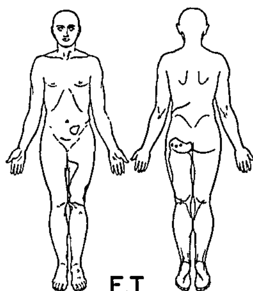
§2. SWEATING PATTERNS AFTER LUMBAR SYMPATHECTOMY

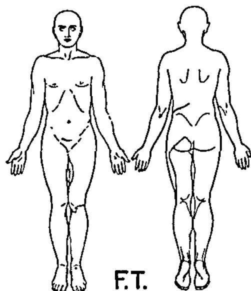
Following on the patterns of thoraco-lumbar sympathectomies, it will now be most convenient to consider those produced by resection of the lumbar paravertebral chain only.

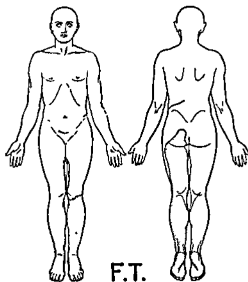
CASE A.P. (Fig. 15). This case, although having undergone resection of the T.12–L.3 ganglia on each side, may best be considered with cases of lumbar sympathectomy. The pattern is essentially the same, as will become evident. This case was first examined eight months or more after operation, and it will be seen that there is no area of anhidrosis on thorax or abdomen. The area of sweating in the perineum is continuous upwards with the area of normal sweating. Carbachol sweat-testing on this occasion showed no anhidrosis anywhere in the lower limbs, indicating that everywhere postganglionic sympathetic neurones were intact even if the lower lumbar and upper sacral ganglia had been deprived of their preganglionic connections.











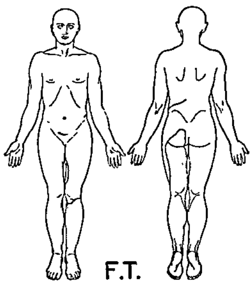


Fig. 15. Cases A.P., F.T.

On testing this patient again two years after operation, essentially the same pattern was observed, showing that there had been almost no recovery of autonomic innervation of the skin except perhaps over an inch or so on the right buttock. No plethysmographic observations were made on this patient.

CASE F.T. (Fig. 15). This shows a continuous series of observations made on a patient who had unilateral lumbar sympathectomy of L.2 and L.3 and possibly the L.4 ganglia (left). When examined nine days after operation it will be observed that there is a small patch of anhidrosis in the lower abdomen which is probably due to section of the ilio-hypogastric nerve in the skin incision. This has been observed in several cases. When present, the patient may complain of soreness in the area, which is typical of the hyperalgesia to be found after section of the sensory branches of a small cutaneous nerve. The lower level of the escape area barely reaches the knee and is rather deficient on the inner thigh. After five months, however, the pattern has become more usual and now shows that the lower edge of the escape area has extended only to L.2 dermatome—at the level of the knee. The patient was examined again at two years and at three years after operation, and sweating patterns show that the area of anhidrosis remained unchanged.

This patient had severe peripheral vascular disease of the left leg. Plethysmographic observations were made before operation and at the time of the last three observations on the sweating area. At all times the blood flow and pulse wave were very small, but at the last occasion, after three years, there was very slight increase in the blood flow of the left big toe on heating the patient.

Fig. 16 shows the observations on five cases, which are particularly relevant to lumbar sympathectomy.

CASE W.R. This shows the usual result of the sweating test obtained after resection of L.2, L.3 and L.4 lumbar ganglia on one side. This patient was examined after four years and shows the typical pattern, which is essentially the same as in Case F.T.

CASE W.T. This is an unusual case in that although L.1, L.2 and L.3 ganglia were resected on the left side, the resultant lower level of the escape area has extended lower than usual into the L.4 dermatome.

This case is particularly instructive in that there were ulcers due to peripheral vascular disease on both sides of the left ankle. After sympathectomy it was observed that the outer edge of the ulcer above the lateral malleolus had healed, but that the ulcer above the medial malleolus still persisted. Only after performing the sweating test did it become evident that autonomic supply was still retained in identically the area of skin which had failed to heal. The portion of the outer ulcer which had healed was surrounded by skin which had now lost its sudomotor supply and therefore, presumably, its vasomotor control. This case shows how important it is to investigate the residual autonomic activity in a patient after sympathectomy.

CASE R.R. This shows the pattern of relative anhidrosis to be obtained after paravertebral injection of procaine into the psoas sheath at the level of L.2, L.3 and L.4 paravertebral ganglia. The local anaesthetic will diffuse around the ganglia and their rami communicantes, and will therefore block the ganglion cells in the intermediate ganglia at this level. It will also diffuse upwards and downwards and, in this case, also seems to have affected the ganglia in relation to the first lumbar nerve root. It will be evident that all the lumbar and upper sacral ganglia have become relatively anhidrotic, and that the upper level of this anhidrosis extends to include L.1 dermatome.

This would be the typical pattern to be expected after paravertebral sympathectomy L.1–L.3 if no intermediate ganglia were present in the upper lumbar nerve roots. This pattern should be compared with all the other cases of lumbar or thoraco-lumbar sympathectomy.

CASE J.D. This case shows the usual pattern to be obtained after L.2, L.3 ganglionectomy.

It will be evident that the sweating pattern is essentially the same whether L.1 ganglion (Cases A.P., W.T., A.D.) or L.4 ganglion (Cases W.R., R.HA., B.E.) is also included.

CASE R.HA. The upper figure shows the pattern of relative anhidrosis observed after spinal anaesthetic which principally affected the right side of the body. It will be observed that the preganglionic outflow of the sympathetic has been blocked from the level of T.1 downwards, though apparently some fibres still remain which synapse with the postganglionic cells to the head and neck. On the left side, however, the preganglionic fibres supplying the postganglionic cells to the cervical and thoracic dermatomes still appear to be unaffected by the anaesthetic. There is therefore a line of demarcation at about the groin which probably includes the L.1 dermatome in the anhidrotic area.

This patient subsequently had resection of L.2, L.3 ganglia on the left, and L.2, L.3 and L.4 on the right. The patterns of the resulting anhidrosis are essentially the same except that it does not extend as high on the right buttock—which was examined four months after operation as compared with three weeks on the left. The patterns are otherwise quite typical.

The inclusion of L.1 on one side has made no apparent difference to the sweating pattern, and no anhidrosis is produced on the front of the thigh—see also Case A.P. (Fig. 15), and Case A.D. (Fig. 19).

GENERAL CONCLUSIONS

All these cases were suffering from peripheral vascular disease, and the blood flows in the great toe were very small even after sympathectomy. Although after sympathectomy the flows in some of them were measured before and after heating the patient, the changes are so slight as to provide no evidence indicating the possibility of recovery of any vasomotor control to the vessels.

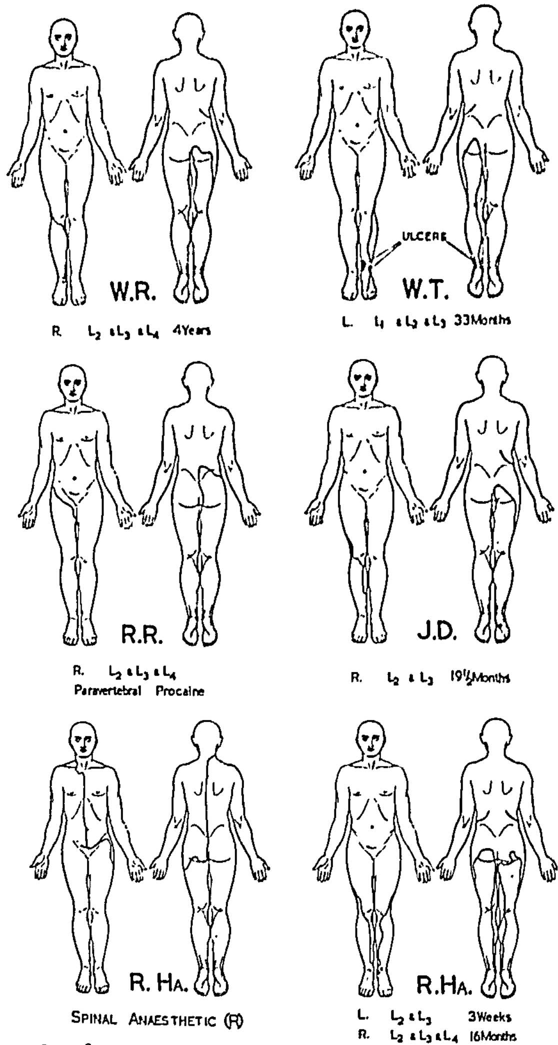


FIG. 16. Cases W.R., W.T., R.R., J.D., R.Ha.

CASE R.R. This shows the pattern of relative anhidrosis to be obtained after paravertebral injection of procaine into the psoas sheath at the level of L.2, L.3 and L.4 paravertebral ganglia. The local anaesthetic will diffuse around the ganglia and their rami communicantes, and will therefore block the ganglion cells in the intermediate ganglia at this level. It will also diffuse upwards and downwards and, in this case, also seems to have affected the ganglia in relation to the first lumbar nerve root. It will be evident that all the lumbar and upper sacral ganglia have become relatively anhidrotic, and that the upper level of this anhidrosis extends to include L.1 dermatome.

This would be the typical pattern to be expected after paravertebral sympathectomy L.1–L.3 if no intermediate ganglia were present in the upper lumbar nerve roots. This pattern should be compared with all the other cases of lumbar or thoraco-lumbar sympathectomy.

CASE J.D. This case shows the usual pattern to be obtained after L.2, L.3 ganglionectomy.

It will be evident that the sweating pattern is essentially the same whether L.1 ganglion (Cases A.P., W.T., A.D.) or L.4 ganglion (Cases W.R., R.HA., B.E.) is also included.

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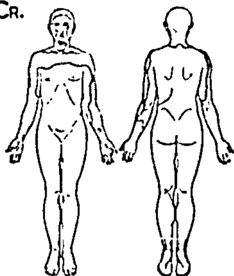
This patient subsequently had resection of L.2, L.3 ganglia on the left, and L.2, L.3 and L.4 on the right. The patterns of the resulting anhidrosis are essentially the same except that it does not extend as high on the right buttock—which was examined four months after operation as compared with three weeks on the left. The patterns are otherwise quite typical.

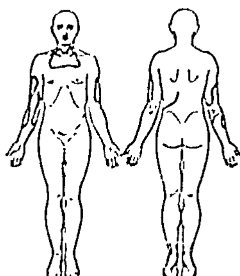
The inclusion of L.1 on one side has made no apparent difference to the sweating pattern, and no anhidrosis is produced on the front of the thigh—see also Case A.P. (Fig. 15), and Case A.D. (Fig. 19).

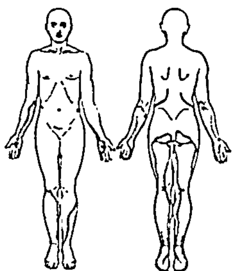
GENERAL CONCLUSIONS

All these cases were suffering from peripheral vascular disease, and the blood flows in the great toe were very small even after sympathectomy. Although after sympathectomy the flows in some of them were measured before and after heating the patient, the changes are so slight as to provide no evidence indicating the possibility of recovery of any vasomotor control to the vessels.

D.Cr.







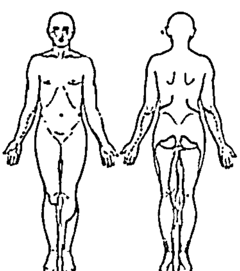


Fig. 17. Case D.Cr.

A year later bilateral lumbar sympathectomy was performed—L.2, L.3 ganglia being resected on each side.

On re-examination after a further year it was evident that autonomic control of the sweat glands had recovered in both upper limbs and head and neck, except possibly for two bands along the ulnar borders of both forearms. Slight sweating was apparent here, and nowhere was there complete anhidrosis, but the margin appeared to correspond to part of the T.1 or C.8 dermatomes.

The bilateral Horner's syndrome was still apparent, but considerably less than on the first observation.

The patterns after lumbar sympathectomy are in every way comparable with those found on the lower limbs after thoraco-lumbar sympathectomy.

When the first lumbar ganglion is resected, the pattern of anhidrosis is essentially the same as that when the resection reaches only as high as the second lumbar vertebra. There would therefore appear to be no advantage in carrying lumbar sympathectomy as high as L.1. It is much more important to ensure that the lower level of the sympathetic preganglionic outflow is completely severed—and therefore the resection should be carried down at least to the level of the middle of the third lumbar vertebra.

§3. SWEATING PATTERNS AFTER FOUR-QUARTER SYMPATHECTOMY

Figs. 17, 18 and 19 show the patterns obtained when cervico-dorsal and lumbar sympathectomies were performed on the same patient, though there was usually an interval of a year or so between the different types of operation.

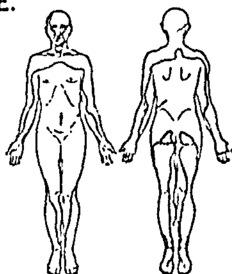
CASE D.CR. This patient had Raynaud's disease affecting principally the fingers. The first operations were resections of stellate and T.2 ganglia on each side by an anterior approach. One month after operation it was found that anhidrosis was present on the arms and trunk, which included the lower level of T.1 dermatome on the left and possibly slightly lower than T.1 on the right. The head and neck were similarly anhidrotic, with the exception of a central mask of the face which included part of the forehead, around the eyes, the sides of the nose and the upper and lower lips. There was also a patch of sweating in front of the larynx. This pattern of sweating on the face was invariable in all cases after cervico-dorsal sympathectomy and is afterwards referred to as the 'central mask' area. The area of sweating in front of the larynx was present in about half the cases examined.

It should be remarked, however, that the skin resistance anywhere on the upper limbs or head and neck, even soon after cervico-dorsal sympathectomy, is never as high as it is in the L.4–S.2 dermatomes of the leg at any time after lumbar sympathectomy.

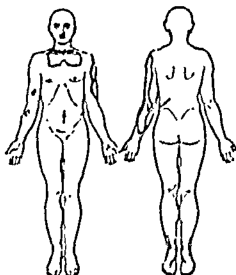
Carbachol testing at this time showed anhidrosis only in small areas. There was a relatively well-demarcated area in the lower neck and upper central part of the thorax in front, which was probably due to section of the medial branches of the supraclavicular nerves in the skin incision. There was also some suggestion of patchy and indefinitely demarcated anhidrosis which corresponded possibly to portions of the 5th or 6th cervical and 1st thoracic dermatomes. Obviously these are incomplete.

A well-marked Horner's syndrome was present on each side.

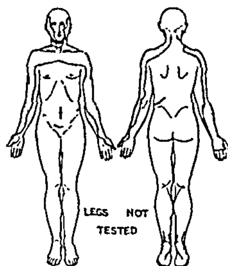
B.E.



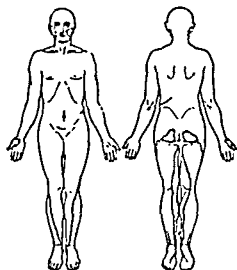
L. St & T2 4 Weeks
L2 L3 L4 12 Years
R. St & T2 5 Weeks
L2 L3 L4. 12 Years



L St & T2 4 Weeks
L2 L3 L4 12 Years
R St & T2 5 Weeks
L2. L3 L4. 12 Years
After Carbachol



L. St & T2 5½Months
L2L3L4 12 Years
R St & T2 5¾ Months
L2 L3.L4 12 Years



L St & T2 20¾Months
L2 L3 L4 13 Years
R St & T2 21 Months
L2 L3 L4 13 Years

Fig. 18. Case B.E.

The anhidrosis due to the lumbar sympathectomy was quite typical. The lower border of the escape area reached below the knees on both sides into L.3. dermatomes—rather lower on the right side.

This case was examined on a further occasion almost three years after the cervico-dorsal operation and over two years after the lumbar sympathectomy. The area of anhidrosis was still present on both forearms but was still indefinite. Both cheeks also appeared to be sweating less than elsewhere on the face—this had not been noted at earlier observations.

The Horner's syndrome was no longer detectable on either side.

The area of anhidrosis resulting from lumbar sympathectomy remained unchanged.

Plethysmography had been performed on the index fingers at each examination. On the first occasion it was evident that vasomotor resection had never been complete. Both blood flow and pulse wave increased on heating the patient. On the second occasion very similar results were obtained, and on the last occasion there was a marked increase in blood flow on heating the patient.

It is evident, therefore, that in the upper limbs, autonomic control both of sweat glands and of blood vessels had returned soon after operation, whereas, in the same patient, the effect on the sweat glands of the lower limbs showed no such recovery.

CASE B.E. This patient had sustained a lumbar sympathectomy twelve years before examination. On the right side it had been performed through a median abdominal [illegible] on.
In both cases the I [illegible]

A resection of tl [illegible] ide through an anterior incision.

One month later thermoregulatory sweating tests showed that the anhidrotic area on the face, head and neck was relatively similar to the previous case, except that it was not so complete along the ulnar borders of the arms. The lower level of the anhidrotic area appeared to include the T.1 dermatome on the left, but the palm of the right hand was sweating, and the lower level of resection may therefore be regarded as possibly C.8. The sweating area on the central mask of the face included rather more of the forehead, especially on the left side. Sweating was again present over the larynx.

Bilateral Horner's syndrome was present after this operation.

Although twelve years had elapsed since the lumbar sympathectomy, the pattern was entirely typical of cases examined after a far shorter interval. The lower edge of the escape area extends well down on the inner sides of the calves to include L.3 dermatomes on both sides. The area of anhidrosis over the buttocks is rather small and appears to be separated from the rest of the S.2 dermatome in the natal folds.

Carbachol sweat-testing at this time showed anhidrosis only in the central part of the upper thorax in the region which was supplied by the supraclavicular nerves after they had been divided at operation. There was also a patch of relative anhidrosis along the left arm, corresponding approximately to part of the C.6 dermatome, and two small 'islands' on the front of the right arm.

from the first observation and had now persisted as a typical pattern for thirteen years! Horner's syndrome was just apparent on the right side, but had recovered completely on the left.

Plethysmography on the index fingers was performed on the first and last occasions. On the left side shortly after operation it appeared that autonomic denervation of vessels had been complete. On the last occasion the blood flow on the left side increased on heating the patient. On the right side it was evident that the autonomic vasomotor control had never been removed; and on the last occasion, on heating the patient, blood flow increased still further, indicating that the vasomotor supply had also increased.

Four other cases of four-quarter sympathectomy are illustrated in Fig. 19.

CASE C.D. Lumbar sympathectomies were performed first on this patient—L.2, L.3 ganglia being resected on each side. Two years later, cervico-dorsal sympathectomy of T.2, T.3 ganglia were resected on each side. It is apparent that the anhidrotic area following cervico-dorsal sympathectomy is of very limited extent, consisting of a band across the front of the upper trunk and down on the outer border of the left arm—it does not extend onto the right arm. The lower border of this anhidrotic area therefore appears to include C.8 on the left, but probably only C.4 on the right. The C.3 dermatomes on each side appear to be intact. It should be noted that on the right side the pattern of anhidrosis closely corresponds to Foerster's C.4 dermatome of residual sensibility. There was no Horner's syndrome.

The anhidrotic area resulting from lumbar sympathectomy is quite typical and includes the L.3 dermatome—being rather lower on the left side. It is almost identical with that observed on the first occasion shortly after operation (not illustrated) except that sweating is apparent on the upper part of the left buttock.

Plethysmography was performed on both fingers and toes. Shortly after the cervico-dorsal operations it was observed that on heating the patient there was no increase in blood flow of the fingers on the right, but that there was slight increase on the left. It therefore appears that vasomotor denervation on the left was never complete.

Blood flow estimations on the toes showed slight increase after heating the patient both on the first occasion, examined shortly after operation, and again two years later. This observation, even of slight increase in blood flows after lumbar sympathectomy, was exceptional. There is, however, some return of sudomotor innervation to the left buttock. Possibly, therefore, there may be minimal recovery of function or incomplete denervation of the autonomic supply on this side.

CASE A.D. Bilateral stellate ganglionectomy had been performed nearly two years before. At about the same time, lumbar sympathectomy of L.2, L.3 ganglia on the left and of L.1, L.2, L.3 ganglia on the right had been performed.

When examined more than eighteen months after these operations it was evident that the sweating patterns resulting from the cervico-dorsal operations were quite dissimilar. Sudomotor supply to the left arm was everywhere com-

On re-examination, nearly six months after the cervico-dorsal sympathectomy, certain changes were observed in the area of anhidrosis on the upper limbs. That on the right was relatively unchanged, but on the left, recovery of autonomic control to the sweat glands had returned in the T.1 and possibly C.8 dermatomes. The area of sweating on face and neck were relatively unchanged.

In order to try to determine further the pathway to the patch of sweating in front of the larynx, certain nerves were injected with 2 per cent. procaine hydrochloride. Since it was known that the facial nerve contains autonomic fibres, it was thought possible that the cervical branch of the facial, which ordinarily supplies the platysma, might contain sudomotor fibres to the skin over the larynx. This branch of the facial was blocked with local anaesthetic, but no change in the skin resistance over the larynx was observed.

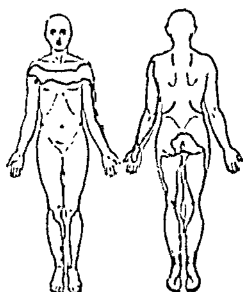
An injection of local anaesthetic was then made into the region of the right anterior cutaneous nerve of the neck, and anaesthetic also infiltrated under this small patch of sweating. Within half a minute it was found that the skin resistance of this patch increased on that side up to the mid-line. It was nowhere absolutely high, nor indeed is it ever to be observed that a local anaesthetic block of a cutaneous nerve produces a very high electrical skin resistance such as is apparent after complete sympathectomy.

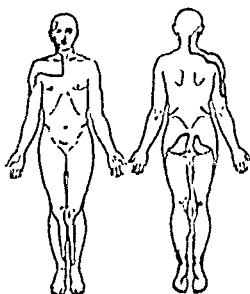
It appears therefore that the area of skin over the larynx, though it may receive sympathetic fibres from the cervical sympathetic chain, with preganglionic fibres passing through the inferior cervical ganglion, receives also sudomotor fibres in a pathway from the brain stem or cord which does not pass through the region of the inferior cervical ganglion. This pathway must be nervous and not humeral, and possibly the peripheral course is with some branches of the cutaneous nerve supply to the area. It is interesting to observe that the area involved is identical with that which Head (1894—*page 426*) has suggested as the cutaneous area associated with the superior laryngeal nerve, and which Frazer (1927) has shown to be developed from the ectoderm of the 3rd branchial arch. Its possible connections with the epibranchial placodes associated with the 9th and 10th cranial nerves will be discussed later when sweating on the face is considered more fully in Chapter 11.

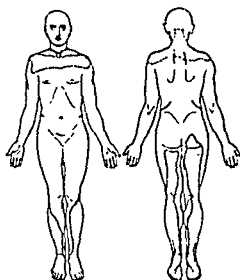
The legs were not tested on this occasion.

This case was examined on the third occasion nearly two years after cervico-dorsal sympathectomy. Two patches of relatively high skin resistance were observed on the cheeks. As in Case D.CR., there was also a patch of increased skin resistance over the thumb on the right side, but elsewhere sudomotor activity had returned to the whole of the upper limbs and head and neck.

The anhidrotic area due to lumbar sympathectomy was quite unchanged







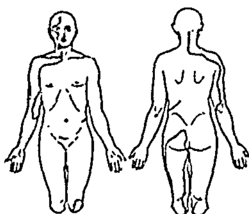


Fig. 19. Cases C.D., A.D., A.A., G.H.

plete. On the right side, however, a patch of relative anhidrosis remained on [illegible]
on either side.

Although lumbar sympathectomy had included one ganglion higher on the right side, the pattern of anhidrosis is quite symmetrical—the lower border of the escape area extends into L.3 dermatome on each side.

Plethysmography was performed on the index fingers when examined almost eighteen months after operation. On the left side it was evident that there was a full recovery of vasomotor control, but on the right side this did not appear to have occurred. There was no increase in pulse wave or blood flow on this side on heating the patient. As sudomotor control had returned to the lower arm, this seemed particularly unusual. It has been observed that vasomotor tone may show recovery when there is no evidence of recovery of sudomotor tone. It is now evident that the reverse can also occur, and that vasomotor tone may still be absent when sudomotor fibres are active. This confirms the conclusions of Felder, Simeone, Linton and Welch (1949). No plethysmography was performed on the toes.

CASE A.A. This case had symmetrical resections T.2, T.3 and L.2, L.3 ganglia on each side.

The case was not examined until over two years after the lumbar sympathectomy and nearly four years after the cervico-dorsal. By this time almost all sweating activity had returned to the arms except in an area of slightly increased skin resistance, which was approximately the same as that observed on Case C.D. (right side). No Horner's syndrome was apparent.

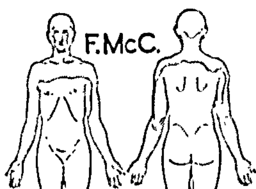
The pattern of anhidrosis resulting from the lumbar sympathectomy was quite typical except that some recovery was apparent on the left buttock. This should be compared with Case C.D. The lower level of the escape area extended well down to the level of the medial malleoli in L.3 dermatomes.

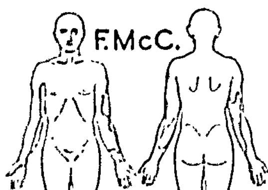
Although plethysmography was performed on the index fingers, the results are probably misleading. On the right side the blood flow was at all times very small due to severe peripheral vascular disease, and on the left side there was only a slight increase on heating the patient, probably due to the fact that he was examined on a very hot day and the vessels on this side were fully dilated before heat was applied to his body.

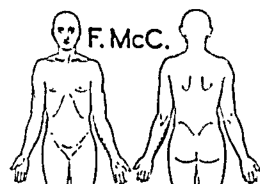
CASE G.H. This case had undergone L.2, L.3 ganglionectomy on the left four years before and a recent stellate and T.2 ganglionectomy on the right. After the lumbar sympathectomy, both legs had been amputated below the knee for peripheral vascular disease. The level of anhidrosis resulting from the cervico-dorsal sympathectomy is quite typical and the lower level includes the T.1 dermatome (compare with Case R.D.—see below). Horner's syndrome was evident on this side.

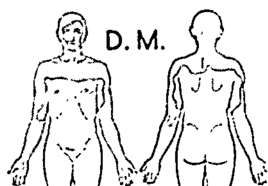
From what can be judged of the pattern of anhidrosis to be seen following lumbar sympathectomy, it is quite typical.

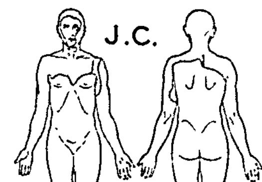
No plethysmography was performed on this patient.

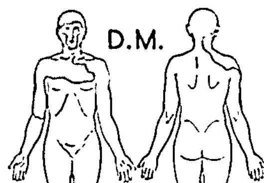


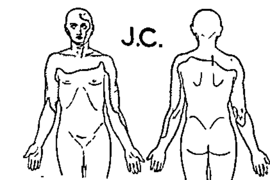












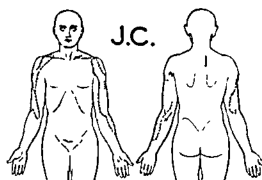


FIG. 20. Cases F.McC., D.M., J.C.

GENERAL CONCLUSIONS

After studying the patterns of anhidrosis obtained after four-quarter sympathectomies, it is evident that the patterns of cervico-dorsal and lumbar sympathectomy, when each is considered separately, are quite typical. In the same patient the pattern of lumbar sympathectomy is permanent, whereas that after cervico-dorsal sympathectomy does not persist. Although plethysmographic observations are not as complete in these six cases as they are in others, it appears that although the upper limbs showed evidence of persistance of a little vasomotor activity, constrictor innervation of blood vessels in the lower limbs, if initially complete, does not return. Later, vasoconstrictor innervation usually returns to the upper limbs at the same time as does the sudomotor innervation. In the lower limbs, sudomotor innervation does not return, even at periods of up to twelve years after operation.

§4. SWEATING PATTERNS AFTER CERVICO-DORSAL (CERVICO-THORACIC) SYMPATHECTOMY

Fig. 20 shows patterns obtained on observation shortly after operation and on later occasions, in three cases who had undergone cervico-dorsal sympathectomy.

CASE F.MCC. This case had stellate and T.2 ganglionectomy performed on each side through an anterior incision for hyperhidrosis of the hands. The lower level of the anhidrotic area is slightly lower on the right than it is on the left. It probably extends into T.1 dermatome on the left and almost to T.2 on the right. Its upper extension includes all the head and neck except for the central mask area. Horner's syndrome was present on each side. Carbachol examination on the same occasion shortly after operation showed anhidrosis only in the hands and on the ulnar border of the right arm and outer border of the left arm, but even here it was very patchy with indefinite edges. It probably indicates that some of the ganglion cells in the T.2 and T.1 dermatomes have been functionally resected. Strangely, in this case, there was no anhidrosis in the area supplied by the supraclavicular nerves, although they might be expected to have been divided in the skin incision.

On further examination a year and a half after operation, it was evident that sudomotor activity had returned to all areas except possibly the ulnar border of the left arm where the skin resistance was slightly higher than on [illegible]

[illegible]

[illegible]

months, however, blood flows and pulse waves on both sides showed marked increases after heating the patient.

When examined again two years after the operations the thermoregulatory sweating pattern showed that some activity of sudomotor fibres had returned to the ulnar borders of the left arm and to the whole of the right forearm. The margins, however, were less definite than on the first occasion and the non-sweating area was only relatively anhidrotic. Sweating on the right-hand side of the face was more extensive, and continued into the central mask area. Horner's syndrome was no longer evident.

Carbachol sweat-testing on this occasion showed only some relative anhidrotic patches on the outer sides of both upper arms. These patches might possibly agree with the 6th cervical dermatomes.

Plethysmographic observations on the index fingers showed that shortly after operation heating the patient caused a decrease in blood flow on the left and a slight increase in flow on the right. Two years later there was marked increase in flow on both sides.

It is therefore evident that on the left side sympathetic resection was initially complete but not so on the right. This might possibly be associated with the higher extent of sympathectomy on the left which also included the stellate ganglion on this side.

Fig. 21 shows the pattern found in three special cases of sympathectomy.

CASE R.D. This case of peripheral vascular disease had a resection of stellate and T.2 ganglia on each side. Two months after operation the pattern of anhidrosis was asymmetrical and included T.1 dermatomes on each side. The central mask of the face was sweating, as is usual. Sweating was also detected around the left external auditory meatus but not the right. Horner's syndrome was present on each side.

Carbachol sweat-testing on this occasion showed only patchy areas of relative anhidrosis principally on the ulnar borders of both forearms—presumably mostly in C.8 and T.1 dermatomes. Although the operations had been performed by an anterior approach, no anhidrosis was evident on the upper trunk in the region supplied by the supraclavicular nerves, although they might be expected to have been sectioned at the operations. Pleth[illegible] y very small [illegible] heating the patient, these changes are too small to be relevant. It appears, however, that vasomotor denervation was complete.

CASE M.M. (Fig. 21). This case of Raynaud's disease, with Case J.C., *v.s.*, are the only ones in this series which were examined shortly after operation for T.2, T.3 'preganglionic section' according to the Smithwick technique.

On each side T.2, T.3 ramisectomy was performed by a posterior approach.

One week after the operation on the left, and four months after operation on the right side, it is evident that the anhidrotic area is not symmetrical, but extends farther down—possibly to T.3 dermatome on the left, but only to T.2 on the right. Sweating occurs on the central mask area of the face, and on the right side is continuous with a tongue of sweating which has extended

It was evident that vasomotor innervation had returned at the same time as the sudomotor innervation. Clinically the patient was very satisfied with the operation. Her hands were not too dry for comfort and the distressing hyperhidrosis had been relieved.

CASE D.M. This case had a similar stellate and T.2 ganglionectomy on each side performed for Raynaud's disease. At the operation on the left side the subclavian artery was injured and subsequently thrombosed. The area of anhidrosis is relatively similar but more symmetrical. The lower edge of the anhidrotic area includes T.1 dermatomes on each side. It extends upwards to include all head and neck, with the exception of the central mask of the face which is rather more extensive on the left forehead than on the right. Horner's syndrome was only moderately evident on each side.

This case was examined again almost a year after operation. The remaining anhidrotic area is asymmetrical and persists in the outer part of the face and neck, in the upper part of the right arm and shoulder, but nowhere on the left arm except on an area below the clavicle. It is evident that sudomotor activity has returned to the greater part of the left cervical and thoracic dermatomes and to the lower cervical and thoracic dermatomes on the right. Sweating was present over the larynx, where probably it had passed unrecognized at the first examination. Horner's syndrome was no longer evident.

Plethysmography performed on the index fingers in this case showed a decrease in the blood flows on both sides on heating the patient at the first examination. On the second occasion there was a slight increase in the blood flow on the right side, after heating the patient, and a more marked increase on the left. On this side, due to thrombosis of the subclavian artery, the blood flow was much less than that on the right, and the pulse wave was only just apparent.

It is evident that in this case, although the levels of sympathectomy were the same, and the initial patterns of sudomotor and vasomotor denervation were identical, recovery of both occurred to a greater extent on the left side than on the right.

CASE J.C. A Smithwick type of 'preganglionic' section of T.2, T.3 rami communicantes had been performed via posterior approach on the right side. Subsequently, stellate and T.2 ganglionectomy was performed by an anterior approach on the left. The patient suffered from severe Raynaud's disease. Shortly after these operations a thermoregulatory sweating test showed almost identical patterns as indicated by the dotted line on the left side. Sweating on the left face was more extensive and no Horner's syndrome was present on this side.

Six weeks after the left operation and two months after the right the lower level of the anhidrotic area appeared to include the T.1 dermatome on the left but extended lower on the right to include T.2. There was, however, a small band of sweating which had now appeared in front of the left shoulder and in the left axilla. The sweating area in the central mask of the face occurred as usual, but was rather more extensive on the right and there was also an area of sweating in front of the larynx on both sides. Horner's syndrome was present on the left but not on the right.

down to include the sweating area over the larynx, and farther across the right shoulder onto the right upper arm. No Horner's syndrome was present on either side.

Carbachol sweat-testing on this patient is of particular interest. If, as according to Smithwick (1936), the second and third thoracic sympathetic ganglia are still viable, and are able to function after being severed from their preganglionic connections and being buried in the muscle tissue of the wound, then it might be considered that carbachol would show no area of absolute anhidrosis. This evidently is not the case. A belt of anhidrosis is present on both sides in front, approximately in the T.1 and T.2 dermatomes. On the back, however, part of these dermatomes seem to have been re-innervated over the right scapula. The general pattern of this area should be compared with that of anhidrosis to thermoregulatory testing as observed in Case C.D. (Fig. 19). It is evident, therefore, that ganglion cells in at least the second thoracic ganglion are *no longer functional* as a result of the operation. Their postganglionic neurones may have been divided on their way to the brachial plexus, but if left intact it is evident that the ganglion cells themselves must have been rendered non-functional as the result of the operation. Presumably, therefore, they are dead. This is not surprising, when the trauma, which this portion of the paravertebral chain sustains, is considered.

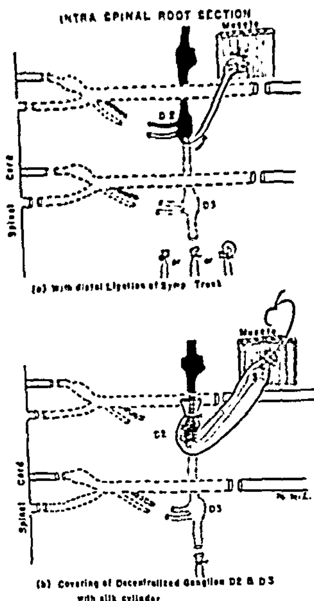
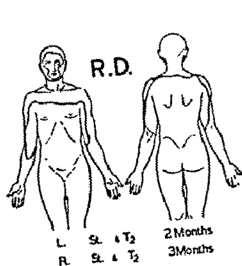
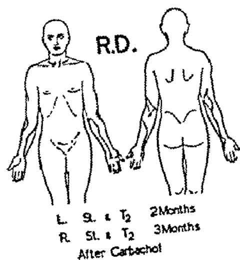
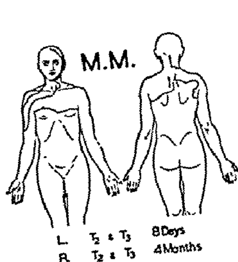


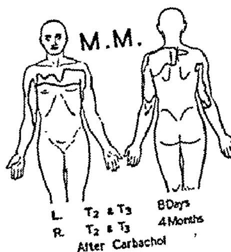
Fig. 22. Operative technique of preganglionic sympathectomy, upper extremity. Smithwick, R. H. (1940) *Ann. Surg.*

The technique of these operations is illustrated in Fig. 22. Although not carried out on this patient, it will be seen that Smithwick recom-









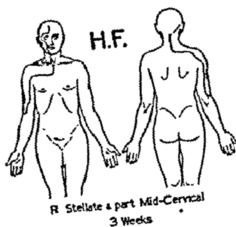


Fig. 21. Cases R.D., M.M., H.F.

though the lower level of the anhidrotic area may show some variation. This may be due to slightly imperfect surgical resection, or possibly to the occurrence of a pre- or post-fixed brachial plexus. It is evident, however, that after a year or so a very considerable degree of sudomotor recovery has taken place in the upper limbs. This is not always so well marked along the ulnar borders of the forearms. This observation would be consistent with the absence of the ganglion cells of the T.1 and T.2 ganglia which ordinarily supply these dermatomes. It appears that in general vasomotor innervation will recover in all cases after this type of operation. Later in this monograph it will be argued that this is due principally to the fact that the upper level of the thoraco-lumbar outflow is not included in an ordinary cervico-dorsal sympathectomy. Preganglionic fibres, therefore, can still pass into the region of the stellate ganglion and can form functional synapses with any ganglion cells in this region which may otherwise have lost their preganglionic connections by reason of sympathectomy at lower levels.

Lumbar sympathectomy does not suffer this disadvantage. The lower level of paravertebral resection includes the lower level of the thoraco-lumbar outflow and therefore all preganglionic fibres are divided. Although ganglion cells may remain intact in the lower lumbar and sacral chain, these are devoid of their preganglionic supply and it is evident that they never recover it. The pattern of a thoraco-lumbar, or lumbar sympathectomy, is permanent; that after cervico-dorsal sympathectomy will invariably recur.

§5. OBSERVATIONS AFTER OTHER FORMS OF NERVE SECTION

ANTERIOR RHIZOTOMY

Fig. 23 shows the patterns obtained from four cases of disseminated sclerosis upon whom anterior rhizotomy was performed in order to relieve painful spasms of the lower limbs. They were all tested before operation for areas of anhidrosis, but these were not detected.

CASE M.PT. This patient had an anterior rhizotomy of T.11–S.1 nerve roots performed simultaneously on each side. Ten days later a thermoregulatory sweating test was made. It appeared that there was an indefinite area of relative anhidrosis corresponding approximately to the usual area found after lumbar sympathectomy. It had a dermatome basis principally affecting L.4, L.5, S.1, S.2 and ?S.3 dermatomes. The distinction was not absolute and the degree of sweating on the shins was also diminished to the naked eye. Indeed obvious visual sweating occurred only down to the level of the lower abdomen, corresponding approximately to the lower edge of T.11 dermatome as indicated by the upper interrupted line.

mends enclosing the T.2 and T.3 gangliform portion of the chain in a silk sheath. Surely in this way they would be entombed as completely as they would have been if resected and placed into a pathological specimen bottle!

The evidence obtained from this case suggests, therefore, that the 'preganglionic' type of Smithwick operation achieves exactly similar functional results as does simple T.2, T.3 ganglionectomy. It may have the slight advantage, however, in that according to Smithwick's original description the T.2, T.3 nerve roots are divided intraspinally. Division of the preganglionic fibres at this level is more certain to prevent regeneration from them than would section in the white rami. These general conclusions are supported by Felder *et al.* (1949), Simeone and Felder (1951) and White, Smithwick and Simeone (1952 —*page 109*).

Plethysmographic observations on this patient indicated that on neither side was vasomotor denervation complete.

CASE H.F. (Fig. 21). This patient underwent sympathectomy for unilateral facial hyperhidrosis. (Reported more fully later.) It was not intended to sympathectomize the hand. The stellate ganglion and a portion of the middle cervical ganglion, and the sympathetic chain between, were resected on the right side through an anterior incision. The lower level of anhidrosis appears to include the C.7 dermatome. (Compare case A.D. *D.S.*). The anhidrotic area is evidently more extensive than that of C.6 dermatome, but does not extend to the palm of the hand which is included in C.8. It is suggested therefore that the lower edge of this anhidrotic area corresponds to the upper edge of C.8 dermatome. Sweating is present over the larynx.

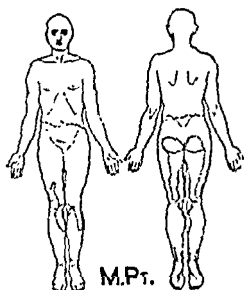
As was to be expected, plethysmographic observations indicated that a large amount of vasomotor control was still present in the index finger on this side.

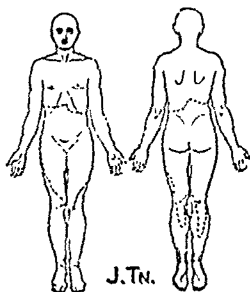
The illustrations of the patterns after the cervico-dorsal sympathectomy do not clearly indicate the accounts of sweating in the region of the external auditory meatus, and below and behind the lobe of the ear. This was observed on the following cases shortly after operation: D.CR., A.D. (right), G.H., J.C., R.D. (left), H.F. That is to say, it was observed to be present on eight sides and absent in nine.

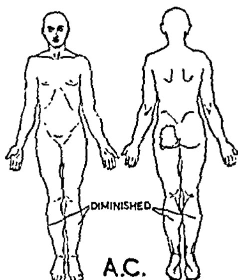
Similarly, sweating over the larynx was observed in these following cases which are not always the same as those in which ear-sweating occurs: D.CR., B.E., A.D. (right and presumably on left), G.H., D.M. (second examination), J.C., M.M. (left and presumably on right), H.F. That is to say, it was observed to be present in fourteen cases and absent in four cases.

GENERAL CONCLUSIONS

These cases of cervico-dorsal sympathectomy confirm the general patterns obtained after four-quarter sympathectomy. When the stellate and T.2 ganglia have been resected, the patterns are very similar al-







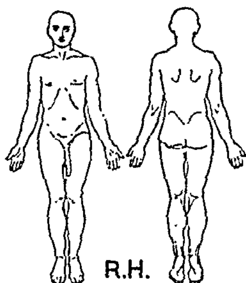


Fig. 23. Cases M.Pt., J.Tn., A.C., R.H. Anterior rhizotomy for disseminated sclerosis.

in patients examined shortly after the operation than those examined later. It would seem, therefore, that new preganglionic fibres from intact levels above those nerve roots sectioned are able to provide a preganglionic supply to the ganglion cells in the lower segments which have been deprived of their original preganglionic synapses by the nerve root sections. In all cases it was evident that sweating was still present in the perineum. The exact amount of this was difficult to

CASE J.TN. This patient also had an anterior rhizotomy of T.11–S.1 nerve roots, but was not fit enough to examine until four weeks later. Again there was an indefinite pattern of relative anhidrosis in the dermatomes below L.3, but there appeared to be more sweating activity on the back of the thigh. Although this does not fit a dermatome basis, there was no absolute anhidrosis and where hypohidrosis is only relative it is difficult to determine where the demarcation should be. Possibly the sacral region on the back of the thigh should have been included. As in the previous case obvious visual sweating occurred down to about T.7 on the right and T.8 on the left.

CASE A.C. This case had anterior rhizotomy of T.12–S.2 nerve roots performed at intervals of three weeks. Three weeks after the second operation a thermoregulatory sweating test was performed. Although sweating on the lower legs was certainly diminished, there was no precise area of relative or complete anhidrosis except for a patch on the left buttock, where it was only relatively apparent.

Plethysmography was performed on the great toes on this occasion. This indicated that before heating the patient, the blood flow on the right (which was the more recently operated side) was considerably greater than that on the left. After heating the patient the flow on the left increased about threefold, and that on the right decreased to approximately the same level—which was about half that on this side before heating. The pulse wave on the right, which was initially about twice as great as that on the left, was relatively unchanged, but that on the left increased to about the same level.

Observations on blood flow after this type of nerve section has been performed were made only on this occasion, and it will be necessary to compare the results obtained in future cases before any conclusions can be made.

Clinical examination after a further three weeks indicated that the right side was no longer as warm or as dry as on the left.

CASE R.H. Anterior rhizotomy T.10–S.2 was performed only on the left side. Five weeks after operation, thermoregulatory testing showed an area of relative anhidrosis extending over the whole of the left leg, with an upper and rather indefinite margin corresponding approximately to the lower edge of the T.12 dermatome except in the perineum. Plethysmographic measurements were not made.

Other more recent observations on two similar cases confirm that the initial hypohidrosis and peripheral vasodilatation are only transient. They are evident at two or three weeks after operation, but after a longer interval it is impossible to recognize any particular pattern of hypohidrosis.

GENERAL CONCLUSIONS

These four cases indicate that section of the preganglionic fibres alone, while the paravertebral chain of postganglionic cells and fibres remains intact, results in areas of only relative anhidrosis. These areas have an approximately segmental distribution, but are more extensive

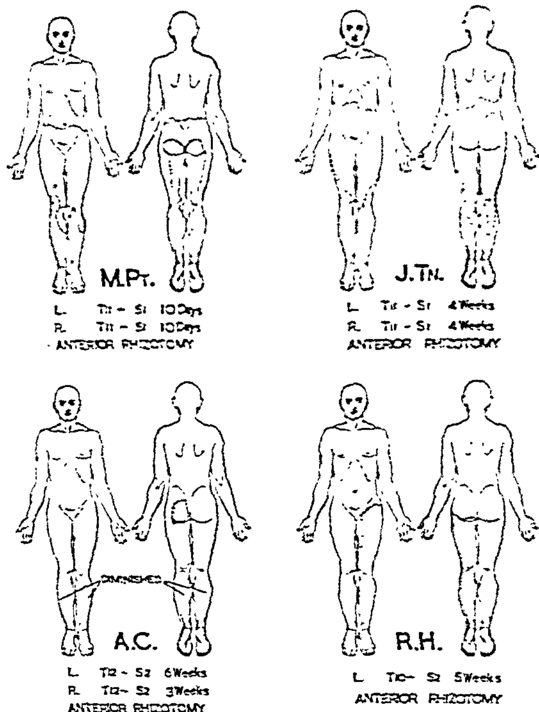


Fig. 23. Cases M.Pt., J.Tn., A.C., R.H. Anterior rhizotomy for disseminated sclerosis.

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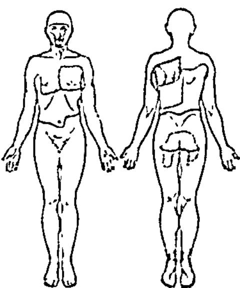
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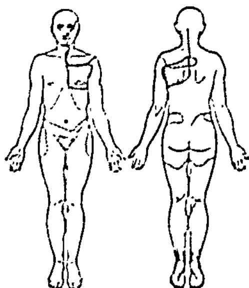
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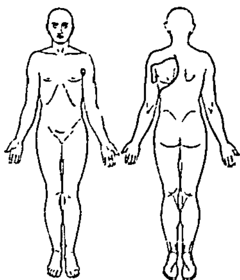




M.K.

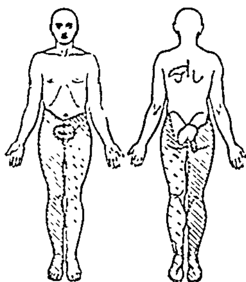
L. T2 – T5 Nerve Section
2 Weeks

L. T2 – T5 Nerve Section
19½ Months



M.Pn.

L. T1 Nerve Section
11 Days



M.T.

L. Cordotomy 1 Month

FIG. 24. Cases M.K., M.Pn., M.T.
(Cross-hatching indicates hypo- or analgesia.)

determine because all four patients were relatively incontinent of urine after operation and two of them had pressure sores on the sacral area.

The author has been searching for other cases with bilateral lesions of the lower sacral nerve roots, but has been able to find none who are continent of urine, have not sores in this area, or who have had a paravertebral lumbar sympathectomy. These cases and the conclusions to be drawn from them were discussed by Monro (1954*a*), and more recently Murray and Thompson (1956 and 1957*a* and *b*) have made experimental observations of collateral sprouting of preganglionic fibres and have even been able to verify this histologically. In this respect they have confirmed for the autonomic nervous system the observations of Edds (1953) on the nerves to muscle.

PERIPHERAL NERVE SECTION

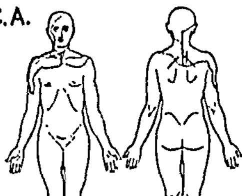
CASE M.K. (Fig. 24). This case is rather difficult to interpret due to the multiple lesions. The initial lesion was due to spinal tumour (extra-dural meningioma) affecting T.2–T.5 nerve roots, on the left side. These nerve roots were sectioned when the tumour was removed. Two weeks later a thermoregulatory sweating test showed almost complete anhidrosis over the whole body except in the upper mid-thoracic region on the right side and the area of ?T.12 dermatome on the left. There was also a patch showing relative sweating over the buttocks and in the perineum. On the left side, almost precisely in the dermatomes where it would be expected, there was diminution of sensation (indicated by cross-hatching). It will be observed that in this case it does not correspond exactly with the area of anhidrosis. Near the mid-line of the back, both analgesia and anhidrosis are present, but towards the axilla, sweating is present, whereas analgesia remains. No Horner's syndrome was present. On re-examination over eighteen months later, sweating activity had returned in part to almost the whole body except for the left side of the head and neck and upper shoulder. The pattern outlined on the lower body shows an indefinite margin of relative anhidrosis. The area of analgesia remains practically identical with that observed on the first occasion, but is slightly smaller in extent where it extends onto the arm. It will be observed that analgesia and anhidrosis are present together only in a small area on the back, but that on the upper shoulder anhidrosis only is present, and over the lower part of the scapula and axilla analgesia only is present.

It is therefore evident that in complicated nerve sections close to the site of the rami communicantes the area of anhidrosis may not always correspond to that of analgesia.

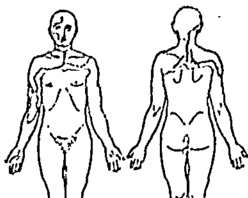
No further follow-up was possible on this patient as she died later that year from a sphenoidal ridge meningioma.

CASE M.PN. This patient had a dumb-bell-shaped neurofibroma of the left 1st thoracic nerve root. There was evidence of slight Horner's syndrome with diminution of sweating on the left side of the face, but nowhere complete anhidrosis. There was no appreciable ptosis nor myosis. A resection of the

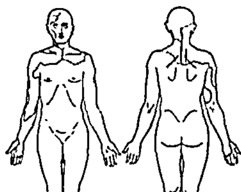
C.A.



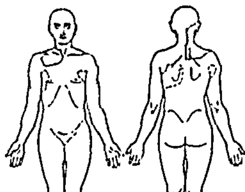
L & R. T_2 T_3 PREGANGLIONIC 12 YEARS
R. REPEATED AT 10, 7, 5 YEARS
R. STELLATE GANGLIONECTOMY 3 YEARS
R MIDDLE CERVICAL GANGLIONECTOMY 1 YEAR



RECOVERY PATTERN 8 WEEKS AFTER 1ST THORACIC ANTERIOR RHIZOTOMY

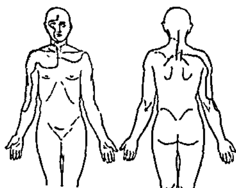


AFTER HEATING

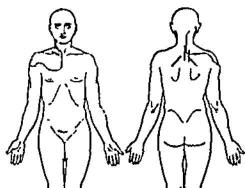


AFTER CARBACHOL

12 DAYS AFTER
R. 1ST THORACIC
ANTERIOR RHIZOTOMY



AFTER HEATING



AFTER CARBACHOL

RECOVERY PATTERN 19½ MONTHS
AFTER 1ST THORACIC
ANTERIOR RHIZOTOMY

FIG. 25. Case C.A. Multiple sympathectomies and anterior rhizotomy.

tumour and part of the nerve root was performed through a curved thoracotomy incision. Eleven days later the sweating pattern showed anhidrosis only in the area of the curve of the incision where the intercostal nerves had been severed. Part of this area may be included in the T.2 dermatome, but obviously T.1 dermatome is principally intact. There was no area of analgesia and no weakness or wasting of the small muscles of the hand.

CASE M.T. Although this case had no true section of a peripheral nerve, the pattern of disturbance of sensation and autonomic innervation of the skin is instructive. Chordotomy of the left lateral spinothalamic tract was performed for the relief of pain in the mid-dorsal region. The typical crossed analgesia is indicated by cross-hatching. Only two areas of relative anhidrosis were detected. There was a small patch at the level of the skin incision on the left side—probably due to local damage to the cord at this level, or possibly due to section of the posterior primary divisions of one or more nerve roots. There was also a relative area of anhidrosis over the back of the sacrum and on the lower abdomen, but this did not extend to the perineum.

In other cases reported in the literature (Johnson *et al.* 1952*a* and *b*) on cases which have undergone high bilateral spinothalamic tractotomy, it has been observed occasionally that anhidrosis was produced on both sides of the body, including the head and neck, to a lesser degree, and with partial Horner's syndrome. The central part of the face and perineum were never involved. It is evident, however, that if the tract is sectioned below the first thoracic segment on one side only, no large area of anhidrosis is produced. This would seem to suggest that the descending fibres to the intermedio-lateral cell column are partly crossed.

FIRST THORACIC ANTERIOR RHIZOTOMY—
WITH SYMPATHECTOMY

CASE C.A. (Fig. 25). This case is of particular interest as it is able to provide information on the upper level of the thoraco-lumbar sympathetic outflow and also a possible explanation for the reasons of recovery of autonomic nerves after cervico-dorsal sympathectomy. This patient had repeated operations for sympathectomy on both upper thoracic regions, but more frequently on the right, all for a similar clinical condition of cyanosis and painful oedema of the right hand. After each operation the clinical condition regularly improved.

When first seen by the author, although no examination was made of the autonomic function at this time, the patient showed evidence of sympathetic activity in the right arm, since the palm of the hand was moist. As will be seen from the legend to the top left figure, stellate ganglionectomy had been performed three years earlier. It was thought that the autonomic supply to the limb might have been passing through the middle cervical ganglion on this side (right).



Fig. 26. First thoracic anterior root. Osmic × 100.



Fig. 27. Degenerated second thoracic anterior root. Osmic × 100.

At operation it was found that the middle cervical ganglion sent a large branch cranially into the superior cervical sympathetic chain. It also sent various rami towards the lower trunks of the brachial plexus, and caudally it was connected to rami which were buried in scar tissue at the site of the previous stellate ganglionectomy. There were also two small (possibly cardiac) branches which passed medially and caudally. The ganglion was resected. The patient showed the usual clinical improvement after operation.

The ganglion removed was fixed in formalin, stained by Weigert's method and examined histologically. Many ganglion cells were present and appeared to be normal, but a few showed changes suggesting degeneration. On one side there was a bundle of autonomic fibres—mostly unmyelinated. On one edge of this there were a number of larger, heavily myelinated fibres which were considered to be sensory in character. It was noticed, however, that the finely myelinated fibres were scattered throughout the whole bundle and that their diameter was about 3–4 microns.

The patient presented herself again with similar symptoms one year later.

Since it was evident that preganglionic fibres were present in the cervical sympathetic chain, it was considered that these may have come either from the intact 1st thoracic nerve root (or from the 8th cervical), or were regenerated fibres that had come from the lower thoracic nerve roots and passed through the scar tissue to form functional synapses with ganglion cells in the cervical region. It was therefore determined to try the effect of a 1st thoracic anterior rhizotomy, with a view to establishing if any of these preganglionic neurones were responsible for the return of autonomic function in the hand. Operation was performed under local anaesthesia. The 1st thoracic anterior nerve root was exposed by a laminectomy and was first stimulated electrically. This caused movement of the small muscles of the hand and also produced slight, but definite, transient vasoconstriction and diminution of the pulse wave in the index finger. After section of the root, the pulse wave increased again in volume.

Histological examination of this anterior root (stained with osmic acid 1 per cent.) showed large numbers of finely myelinated fibres (Fig. 26). At the same time the 2nd and 3rd anterior nerve roots were also sectioned, but it was found that they had completely degenerated as a result of the earlier operations (Smithwick technique), and consisted only of fibrous tissue and a few small blood vessels (Fig. 27). When the 1st thoracic anterior nerve root and the original section through the middle cervical ganglion were re-examined, it was observed that the fine myelinated fibres were of the same size in both—indeed, some may even have been the same fibres!

Sweating patterns were determined both before and after this operation and are illustrated in Fig. 25. Before anterior rhizotomy of T.1, it will be seen that there is an area of anhidrosis on the right side of the head and neck and shoulder which includes the C.4 and part of C.5 dermatomes. There is an indefinite tongue of sweating extending from the area of the larynx across in front of the shoulder (compare Case M.M.). On the left side sweating was reduced over the top of the shoulder and base of neck where indicated by the interrupted lines, but nowhere was there absolute anhidrosis.

On re-testing twelve days after 1st thoracic anterior rhizotomy, it was evident that the area of anhidrosis on the right side had now extended down on the front and inner side of the upper arm, and on the radial side and back of hand. This extension is not typical of any one dermatome, but would be included in parts of C.7?, C.8, T.1, T.2? dermatomes. Carbachol sweat-testing on the same occasion showed an area of anhidrosis in front, only in the region of the right supraclavicular nerves which might have been sectioned by the different operations on the neck, and on the back in part of C.3 or possibly C.4 dermatomes.

Plethysmography on the index fingers on this occasion showed approximately equal blood flow, but after heating the patient there was a slight decrease of flow on the right whereas it was increased on the left.

This should be taken as evidence of recent section of vasoconstrictor nerves having been performed on the right side. Before the operation both sides had showed an increase in blood flow after heating. This had indicated that vasoconstrictor nerves were present.

Shortly after operation the patient was tested with a view to determining whether she had sustained any loss of power in the hand. She stated that she found a little clumsiness with her knitting, but clinically there was no paresis. The electrical reactions of the small muscles of the hand suggested that there was some weakness and diminished response to stimulation in those muscles on the ulnar border of the right hand as compared with those on the left. On subsequent examination two months later the patient stated that she had now no weakness and the electrical reactions showed no difference between the two sides.

Ray (1953) reported three cases in which he had combined cervico-thoracic sympathectomy from the inferior cervical to the 3rd thoracic ganglia, with intradural rhizotomy of the first three thoracic anterior roots. Only one case showed any permanent motor deficit, and Ray thought that this was probably due to a 'post-fixed plexus'.

The patient (C.A.) was examined again two months after her operation—she had remained free of symptoms. The sweating pattern showed that on thermoregulatory testing the area of anhidrosis was very similar to that observed on the first occasion before operation (top left). Sudomotor activity had returned on the front of the arm where it had first been noted shortly after operation (indicated by interrupted line in this area). Plethysmography on the index fingers was repeated. There was now an increase in blood flow after heating the patient. No anhidrosis had remained on the hand.

C.5 dermatome. It was, however, not so absolute as had been noted before. The skin had a lower electrical resistance and was patchy with indefinite borders. It appeared, therefore, that some sudomotor activity was re-establishing itself in at least the area on the arm. Carbachol sweat-testing showed a pattern similar to that noted on the earlier occasion except that it had extended a little farther on the outer part of the shoulder. Plethysmography on the index fingers showed marked increase both in pulse wave and blood flows on heating the patient.

The general inference was that, as appeared to be the usual finding after cervico-dorsal sympathectomy, a certain degree of recovery of function of the sympathetic nervous system was occurring, although with greater difficulty than is usual on account of the greater number of ganglion cells that had been removed by the many operations.

GENERAL CONCLUSIONS

The patterns observed after anterior rhizotomy of nerves leaving at the usually accepted upper and lower levels of the thoraco-lumbar outflow are not permanent: autonomic activity very quickly returns to the areas initially denervated. Functional reorganization by means of collateral sprouting probably takes place within the intact paravertebral chain of sympathetic ganglia. Preganglionic fibres from the lower thoracic nerve roots, which have been left intact, send out sprouts to establish functional synapses with ganglion cells whose original preganglionic supply has been severed. Since these fibres, whose activity persists, have never been injured, the process is rather of functional reorganization than of regeneration: it is an extension of their area of conduction of impulses to ganglion cells. In the cervico-dorsal region, these fibres must come from the 8th cervical anterior root or above.

SEGMENTAL PERIPHERAL NERVE LESIONS—BRACHIAL PLEXUS LESION

CASE E.C. (Fig. 28) shows the patterns obtained from sweating tests and of tests for sensation on three successive occasions.

The patient had sustained an avulsion of the left brachial plexus. Initially there had been a complete loss of all form of sensation and motor power in the left arm, and there was also a left Horner's syndrome. There had also been a suggestion of left phrenic palsy, but this was not confirmed six months later. Following on the injury the patient developed a subluxation of the left shoulder joint due to paralysis of the surrounding muscles.

When first examined seven months after injury, the sweating pattern revealed complete anhidrosis in the whole of the left C.5–T.2? dermatomes, which are supplied from the nerves forming the brachial plexus. The C.4 dermatome appeared to be intact, as also did the T.3, but sweating was apparent in the axilla extending for about 2 inches along the inner arm, and it is possible that this may have comprised part of T.2 dermatome. The margin

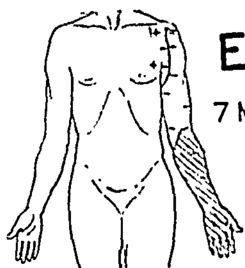
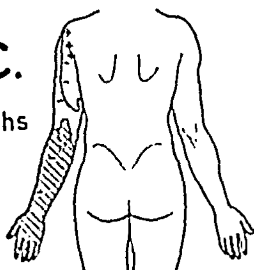
The conclusion after these observations was that the 1st thoracic anterior nerve root had supplied preganglionic fibres which formed functional synapses with ganglion cells present in the ganglia in the cervical regions (intermediate cervical or portions of the cervical sympathetic chain). When the 1st thoracic anterior nerve root had been sectioned, these ganglion cells were no longer under central control and therefore anhidrosis appeared in the area under their sole supply. This included the vasoconstrictor supply to the hand (index finger). Within two months, however, new preganglionic fibres, either from a higher level (8th cervical root or above) or from a lower level (regenerated fibres from 4th thoracic root or below), had established functional connections with these ganglion cells. They were therefore able to re-exert their sudomotor and vasoconstrictor activity in the same areas as they had done before 1st thoracic anterior rhizotomy.

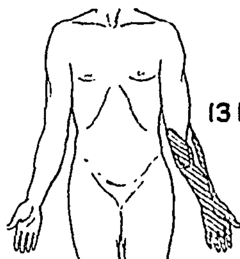
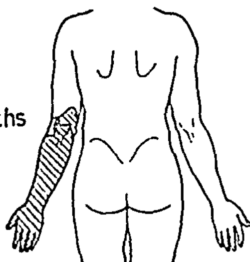
This seemed to provide an opportunity for endeavouring to determine whether the remaining preganglionic fibres came from intact levels from the 8th cervical root or above, or whether they were regenerated fibres from the 4th thoracic or below. Accordingly the patient was given a spinal anaesthetic, with the aim of blocking the anterior nerve roots at least as high as to include T.4 on the right. The level of analgesia reached as high as the lower level of the T.2 dermatome according to Foerster (indicated by a finely dotted line in the diagram). It was therefore probable that the posterior roots of T.3 and T.4 nerves had been anaesthetized. It was not possible to say with absolute certainty, however, that the T.4 anterior root was similarly anaesthetized, for it might have been that the posterior roots were affected to a higher level, and although it was unlikely that this could have extended to more than two nerve roots, the possibility cannot be absolutely discounted.

There was no change in vasoconstrictor control in the index finger. The most likely explanation is that in this case the preganglionic supply on this side, left the cord in the 8th cervical nerve root or higher. In about 50 per cent. of cases the 8th cervical nerve root contains the upper level of the thoraco-lumbar outflow (Sunderland, 1948).

Coldwater, Alexander, Cox and Randall (1957) have found that electrical stimulation of the ramus from the 1st thoracic nerve produces significant sweating in the upper extremity, and Ray (1955) found definite suggestions in the records of his patients at operation that there were positive sympathetic responses from stimulation of the 7th and 8th cervical roots even after the cervico-thoracic chain was removed.

The patient was examined again twenty-one months after the last operation. The sweating pattern showed that on heat testing the area of anhidrosis on the right side remained very similar to that on the previous occasion except that it had extended down slightly on the outer side of the arm in the

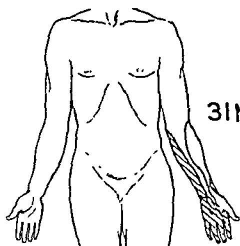
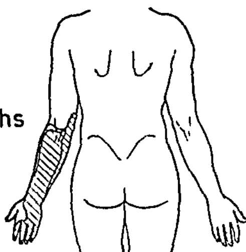



Fig. 28. Case E.C. Anhidrosis shaded, analgesia cross-hatched.

of the anhidrotic area was everywhere very precise. The loss of sensation to fine touch exactly fitted this anhidrotic area, but sensation to pain (scratch) was present on the upper arm down to the level of the elbow where it extends just above the olecranon behind, and rather lower on the medial border of the arm (see Fig. 28).

Carbachol sweat-testing on this occasion showed that the whole of the area which was anhidrotic to thermoregulatory testing was also anhidrotic to carbachol. This indicated that the injury to the sudomotor pathway was distal to the junction of the rami communicantes with the peripheral nerve and that the lesion therefore consisted only of a postganglionic nerve section.

Further evidence of this was obtained by observing the reaction to local electrical stimulation of the skin. Lewis and Marvin (1927) and Lewis and Landis (1930) describe this method for testing the integrity of autonomic nerves in the skin. It is said to be absent when ganglionectomy has been performed at the corresponding level. Local piloerection was evident where it has been marked on the figure with a plus (+) sign, but absent where marked with a minus (−) sign. It will be seen that it is absent just proximal to the upper level of the anhidrotic area both on the front of the shoulder and back of the upper arm. It is present a further 2 or 3 cm. proximal on the front of the shoulder and over the scapula, but is very close to the anhidrotic area at the tip of the acromion.

Plethysmography was performed on the index fingers. The initial blood flows on the left side were very small, although there was no actual peripheral vascular disease. After heating the patient the blood flows decreased still further! The pulse wave showed a slight increase.

The patient was examined again thirteen months after the injury. The upper border of absolute anhidrosis remained very precise, but had now descended to about the level of the elbow and extended farther, half-way down the forearm on the medial anterior aspect. Relative loss of sweating was still apparent on the upper and outer aspect of the arm from the tip of the acromion, but free sweating appeared to have returned to the whole of the T.2 dermatome. Cutaneous sensibility had also extended down the arm. Sensation to pin-prick was now appreciated on the front of the forearm over the shaft of the radius in a thin tongue-like extension as far as the base of the thumb. On the back of the lower part of the upper arm, however, there was an appreciation of light touch but not of pin-prick, and on the inner aspect of the upper arm, pin and light touch sensation were both absent.

Stroking the outer aspect of the upper arm caused marked local piloerection accompanied by a 'burning' pain.

It is evident that on this occasion there has been considerable regeneration of different types of sensory nerve and of the postganglionic nerve fibres, but the growth of these respective types of nerve has not been everywhere the same, and one type only may have grown into one area of skin, and another type into a separate area. On the front of the forearm sensation to pin-prick has extended furthermost and autonomic fibres follow second.

Some experiments of Weddell, Guttmann and Guttmann (1941) should now be reconsidered. These workers found that if they sectioned the sural nerve in a rabbit, the resulting area of sensory loss (autonomous zone) shrank each day until it might eventually disappear—especially in a young animal. If, instead, they sectioned the tibial and peroneal nerves, the area of sensation transmitted by the sural nerve was very much larger (maximal zone). The difference of overlap between these two zones they called the intermediate zone, and they believed it represented the overlap with the surrounding nerves. Unfortunately, the areas investigated all lie in the same or possibly adjacent dermatomes, and it would therefore be interesting to repeat this type of experiment on nerves which have markedly different segmental origins. It is evident that, for autonomic nerves, the intermediate zone common to the L.2, L.3 dermatomes and the S.2 dermatome is very small even if it exists at all. Of course, in the human cases considered here, the sacral post-ganglionic neurones are intact and are deprived only of their pre-ganglionic connections, but in several cases the innervation from the posterior L.2 dermatome on the upper buttock extends into the L.3 dermatome just below it. Presumably the intermediate ganglia at this level remain intact even if the paravertebral chain is resected to a lower level than usual. Indeed, the pattern on first observation may not show sweating in the whole of the dermatome, though it may be more complete later. If no regeneration occurs, it would seem that there is some fundamental impossibility for a sweating pattern to extend beyond the margins of its own dermatome or possibly that segmentally next above or below.

In the thoracic anhidrotic area, where carbachol testing has shown that all ganglion cells were removed at operation, sudomotor fibres from the upper thorax do not encroach into this area for more than one intercostal space.

This principle would lend support to the observations of Sperry (1955) on the biochemical specificity of neurones in respect to sensation and the earlier studies of Weiss (1941) on motor innervation. Sperry suggests that specific factors in the skin of the embryo are arranged on a dorsoventral gradient and thus vary quantitatively, whereas on an anteroposterior (cranial-caudal) gradient they vary qualitatively. Such a conception would seem to apply to the cutaneous autonomic nerves at least in regard to the postganglionic neurones, but if it also applies to the preganglionic fibres and their synapses, then the range of qualitative specificity must cover many more segments.

The whole question of the constancy and occasional dissociation of different forms of autonomic activity in the skin still needs adequate explanation. Some aspects of this have recently been discussed by the author (Monro, 1959).

Plethysmographic observations on the index fingers on this occasion showed similar reduction of blood flow on the left side after heating the patient, but the pulse wave was relatively unchanged, though so small that this observation may not be significant.

The patient was examined on a third occasion thirty-one months after injury. The anhidrotic area to thermoregulatory testing had further decreased in size, but its edge was still quite precise. On the back of the forearm and lateral border it still extended as high as the elbow, but on the front of the forearm and the medial border it had extended as low as the wrist and the skin over the muscles of the thenar eminence.

Sensation to light touch was now present on the whole of the hand and fingers, but there was still dullness to pin-prick along the medial border of the forearm and over most of the hand, except both sides of the thumb. Plethysmographic observations on this occasion showed a change: there was now a slight increase in the blood flow after heating the patient, and the pulse wave also showed slight increase.

After ordinary forms of cervico-dorsal sympathectomy, it is usual for vasoconstrictor control to return to the digits within three months. In this case it is particularly interesting to note that no such control had returned at thirteen months, and it was not until almost three years had elapsed that slight vasoconstrictor activity was regained. It was evident that this recovery of autonomic function was exemplified also in the extension of sudomotor activity to include the base of the thumb. After ordinary cervico-dorsal sympathectomy it is almost invariable for some sudomotor activity to be evident in the hands at three months, or earlier. This case was also exceptional in that the clefts between the fingers, when examined on the first two occasions, were absolutely anhidrotic. This is never found on any case of sympathectomy. Indeed, Netsky and Walker (1947) calculate that at least 2 per cent. of sweat glands on the fingers remain functional even immediately after sympathectomy.

GENERAL CONCLUSIONS

It is certainly possible to produce a complete autonomic denervation of the skin and vessels in the limb if all postganglionic fibres are divided. Autonomic paralysis will remain permanent as long as new nerve fibres do not grow into the denervated area. It is therefore suggested that all forms of recovery of autonomic activity, either sudomotor or vasomotor, are really due to re-innervation and not due to recovery of intrinsic tone of vessels or sweat glands.

A particularly constant feature of these observations is the position of the margin on the outer thigh between sweating in the L.2, L.3 dermatomes and the anhidrosis in the S.2 dermatome. Even over a period of four years or more, the fibres from the lumbar intermediate ganglia do not extend their innervation to the sweat glands even 1 cm. away which lie in the segmentally more distant sacral area.

three months after operation on all 17 sides. Principally due to the severe peripheral vascular disease in these patients, vasomotor activity was only investigated on 3 sides, and on 2 of these it was also determined within 3 months of operation. Blood flow estimations indicated vasomotor activity on 2 sides, one of which showed the same behaviour shortly after operation, and this was probably due to incomplete resection in this respect although the pattern of anhidrosis was quite permanent. Measurements of the height of the pulse wave did not indicate any vasomotor activity.

Table II shows both cases of four-quarter sympathectomy and lumbar sympathectomy alone. *If these observations are combined with those of* Table I the following information can be obtained:

Upper level of escape area	*Sides*	*Per cent. (approx.)*
T.9	1	2
T.10	6	13
T.11	5	11
T.12	16	34
L.1	19	40
	47	

Lower level of escape area		
L.2	9	14
L.3	33	53
L.3+	20	32
L.4	1	1
	63	

(L.3 + indicates a tendency for the dermatome to extend lower on the leg.)

When vasomotor observations in Tables I and II are combined it is evident that if, after heating the body, an increase in blood flow or pulse wave in the digit is taken to indicate *the presence of* vasomotor activity, then:

Vasomotor activity (in toe)	*Present*	*Absent*
Blood flow	12 sides	19 sides
Pulse wave	7 sides	24 sides

Transthoracic resections accounted for 2 sides (D.F.) on which the pulse wave increased, and 3 sides (T.B., D.F.) on which the blood flow increased, to which may be added the side of lumbar sympathectomy

Chapter 6

CONCLUSIONS FROM SWEATING PATTERNS

A SUMMARY of the relevant findings in regard to the levels of the sweating and anhidrotic areas after thoraco-lumbar sympathectomy is given in Table I. This includes symbolic information in regard to the presence of vasomotor activity in the vessels of the toes; this is indicated both in regard to changes in blood flows and in the height of the pulse wave. In five instances there was a decrease in the blood flow after heating the patient: this is indicated by the symbol —D. This phenomenon will be discussed in Chapter 12.

The sweating patterns were examined on 49 sides, but in 9 of these sides observations were not made after three months from the date of operation. In 8 sides the thoracic portion of the paravertebral chain was resected by a transthoracic approach: these are indicated by *T* against the intended levels of resection. In 3 out of these 8 sides, the sweating pattern indicated imperfect resection, and on 2 of them considerable vasoconstrictor tone was present in the toes.

With the exception of these eight cases of transthoracic resection, only one case, after retro-pleural resection, showed any degree of activity on one side shortly after operation. At a later examination, this activity had increased. It is probable that in this case the resection was imperfect, either due to a double lumbar sympathetic chain on this side, or due to an unusually low level of the thoraco-lumbar outflow of the sympathetic preganglionic fibres. Of the remaining 45 sides there were none which showed any sudomotor activity on the feet after periods up to four years.

Observations on the presence of a vasomotor control were made only on cases examined more than three months after operation. After heating the patient, blood flows showed a significant increase on 10 sides, of which 3 were transthoracic cases. Eighteen sides showed no change or a decrease in flow. The pulse wave was increased on 7 sides, of which 2 were transthoracic cases. There was no change of the height of the pulse wave on 21 sides. These figures are aggregated with those cases examined after lumbar sympathectomy. One case (D.CL.) was under treatment with an adrenolytic drug (hydrallazine) and the vasomotor observations are ignored.

A summary of the findings after lumbar sympathectomy is given in Table II. Sudomotor patterns were determined at intervals greater than

E.T.		34	L. T.7 –L.3	T.9	T.12	imperfect		+		
			R. T.9 –L.2	T.10	?T.12	L.2	—	—		
P.F.	m	31	L. T.4 –L.3	T.4	L.1	L.3	—	—	—	—
			R. T.4 –L.3	T.4	T.10	L.3	—	—	—	—
E.I.	m	30	L. T.4 –L.3	T.4	L.1	L.3	—			
			R. T.4 –L.3	T.4	L.1	L.3	—			
E.F.	m	41	L. T.5 –L.3	T.5	L.1	L.3	—	—	—D	—
			R. T.4 –L.3	T.5	T.12	L.3	—	—	+	+
E.H.	f	32	L. T.8 –L.3	T.7	L.1	L.3+	—	—		
			R. T.7 –L.3	T.7	T.12	L.3+	—	—		
V.F.	f	35	L. T.2 –L.3	T.2	T.12+	L.3	—	—	—D	—
			R. T.4 –L.3	T.3	T.12+	L.3	—	—	—D	—
M.R.	f	48	L. T.6 –L.3 *T*	T.7	T.12	L.3	—	—	—D	—
			R. T.6 –L.3 *T*	T.7	T.12+	L.3	—	—	—D	—
T.B.	m	32	L. T.6 –L.3 *T*	T.7	T.11	L.2	—	—	+	—
			R. T.6 –L.3 *T*	T.7	L.1+	L.2	—	—	—	—
D.Cl.	f	33	L. T.6 –L.3 *T*	T.6	T.11	L.2	—	—	?*	?*
			R. T.6 –L.3 *T*	T.8	L.1	imperfect	—?	—?	?*	?*
D.F.	m	24	L. T.6 –L.3 *T*	imperfect	imperfect	imperfect	—?	—?	+	+
			R. T.6 –L.3 *T*	T.6	T.12	imperfect	—?		++	+
S.W.	m	52	L. T.8 –L.3	T.12	T.9	L.3	—	—		
			49 sides		*Sympathetic activity*	Present	1 certain (?4)		10(3*T*)	7(2*T*)
						Absent	45		18(3*T*)	21(4*T*)
						Totals	49(8*T*)		28(6*T*)	28(6*T*)

Sudomotor patterns were not followed up after three months on 9 sides.

Key. L.3+ indicates a tendency for the dermatome to extend lower on the leg.
T indicates a transthoracic resection.
D indicates decrease in blood flow after heating the body. Total = 7.

* Vasomotor observations on Case *D.Cl.* not included—see Table IX.

Table I.—THORACO-LUMBAR SYMPATHECTOMY

Case	Sex	Age	Levels of intended resection	Upper level of anhidrotic area (ganglion resected)	Upper level of escape area (ganglion present)	Lower level of escape area (ganglion present)	Sudomotor activity on foot		Vasomotor activity in toe	
									Late only	
							Early	Late	Flow	Pulse
E.R. .	f	24	L. T.8 –L.3	T.8	L.1	L.3	–	–		
			R. T.8 –L.3	T.9	T.11	L.3	–	–		
A.T.	f	41	L. T.8 –L.3	T.9	T.12	L.3	–	–		
			R. T.8 –L.3	T.9	T.12	L.3	–	–		
B.S.	f	27	L. T.9 –L.3	T.9	L.1	L.3+	–	–	–	+
			R. T.8 –L.3	T.7	T.10	L.2	–	–	+	–
D.McM.	f	46	L. T.4 –L.3	T.3	L.1	L.3+	–			
			R. T.4 –L.3	T.10	L.1	L.3+	–			
S.S. .	f	34	L. T.8 –L.3	T.7	T.12	L.2	–			
			R. T.4 –L.3	T.7	L.1	L.2	–			
W.P. .	m	41	L. T.4 –L.3	T.3	T.12	L.3	–			
			R. T.4 –L.3	T.3	T.10	L.3+	–			
Mn.B.	f	32	L. T.5 –L.3	T.5	T.11	L.3+	–	–	–D	–
			R. T.5 –L.3	T.5	T.10	L.3+	–	–	–D	–
E.P.	f	54	L. T.4 –L.3	T.5	L.1	L.3	–	–	+	–
			R. T.4 –L.3	T.5	T.10	L.3	–	–	–	–
K.F.	f	54	L. T.11–L.3	T.10	L.1	L.3	–	–		
			R. T.11–L.3	T.10	L.1	L.3+	–	–		
W.S. .	m	31	L. T.10–L.3	T.10	T.12	L.3+	–	–	–	+
			R. T.4 –L.3	T.4	T.11	L.3	–	–	+	–
L.C. .	f	37	L. T.4 –L.3	T.4	T.10	L.3+	–	–	–	–
			R. T.4 –L.3	T.4	L.1	L.3+	–	–	–	–
J.T. .	m	33	L. T.5 –L.2	T.5	T.12	L.3	–	–	+	–
			R. T.5 –L.3	T.5	T.12	L.3	–	–	–	–
Mt.B. .	f	10	L. T.9 –L.2	T.9	L.1	L.3	–	–	+	+
			R. T.7 –L.3	T.8	L.1	L.3	–	–	+	+
W.D.	m	47	L. T.4 –L.3	T.4	L.1	L.2	–	–	–	–
			R. T.4 –L.3	?T.2	L.1	L.?				

Table III.—CERVICO-DORSAL SYMPATHE…

Case	Sex	Age	Intended levels of resection of ganglia	Lower level of anhidrotic area	Early sudomotor activity (0–3 months): Central face	Early sudomotor activity: Ear	Early sudomotor activity: Larynx	Sympathetic activity, Early (0–3 months): Hand sudomotor	Early: Eye sympathetic	Early: Vasomotor activity, Flow	Early: Vasomotor activity, Pulse	Late (over 3 months): Hand sudomotor	Late: Eye sympathetic	Late: Vasomotor activity, Flow	Late: Vasomotor activity, Pulse
Four-Quarter															
D.CR.	f	46	L. St. T.2	T.1	+	+	+	—	—	+	+	+	+	+ +	+ +
			R. St. T.2	T.1 +	+	+	+	—	—	+	+	+	+	— +	— +
B.E.	f	33	L. St. T.2	T.1	+	—	+	—	—	—	—	+	+	+ —	
			R. St. T.2	? C.8	+	—	+	—	—	+ +	—	+	+ —	+ +	+
C.D.	f	52	L. T.2 T.3	C.8	+	? +	? +	? +	+s	+	+				
			R. T.2 T.3	? C.4	+	? +	? +	+	+s	—	—				
A D.	f	29	L. St.	nil		(late only)						+l	+	+ —	+ +
			R St.	? C.7		(late only)						+l	+	—	—
G.H.	m	38	R. St. T.2	T.1	+	+	+	—	—						
Cervico-dorsal															
F.McC		29	L. St. T.2	T.1	+	—	—	—	—	—	—	+	+ —	+ +	+ +
			R. St. T.2	T.1	+	—	—	—	—	—	—	+	+	+ —	+ +
D.M.	f	22	L. St. T.2	T.1	+	—	? +	—	—	— D	— D	+	+	+ +	+ +
			R. St. T.2	T.1	+	—	? +	—	—	— D	—	+	+	—	? —
J.C.	f	16	L. St. T.2	T.1	+	+	+	—	—	— D	—	+	+	—	
			R. T.2 T.3	T.2	+	+	+		+s	+		+	+s	—	
R.D.	m	58	L. St. T.2	T.1	+	+	—	—	—	— D	— D				
			R. St. T.2	T.1	+	—	—	—	—	— D					
M.M.	f	26	L. T.2 T.3	? T.3	+	—	+	—	+s	+					
			R. T.2 T.3*	T.2	+*	—	+*					—*	+*	+*	—*
H.F.	f	47	R. St. and Middle Cervical	? C.7	+	+	+	+l	—	+ +	+ +				
20 sides			*Sympathetic activity*	Present	18	7 (? 9)	10 (? 14)	1(?2) (l)	0 (s)	7	4	10 (2l)	(10 2s)	12	7 (? 8)
				Absent	0	9	4	13	13	9 (5D)	10 (2D)	1*	0 (2 ±)	1	2
				Totals	18	18	18	16	13	16	14	11	10	13	10

Key. * first examined at 4 months after operation: observations on face presumed to be the same at under 3 months. Vasomotor observations suggest early recovery of vasomotor control at 4 months. s stellate ganglion not included in resection; observations on eye not included in total. l neither T.1 nor T.2 ganglion included in resection; observations on hand not included in total.

Table II.—LUMBAR SYMPATHECTOMY

Case	Sex	Age	Levels of intended resection	Lower level of escape area	Sudomotor activity on foot		Vasomotor activity in toe			
							Early (0–3 months)		Late (over 3 months)	
					Early	Late	Flow	Pulse	Flow	Pulse
Lumbar										
A.P.	f	53	L. T.12–L.3	L.3+	—	—				
			R. T.12–L.3	L.3+	—	—				
F.T.	m	59	L. L.2–L.3–(L.4)	L.2	—	—				
W.R.	m	51	R. L.2–L.3–L.4	L.3	—	—				
W.T.	m	45	L. L.1–L.2–L.3	L.4	—	—				
J.D.	m	55	R. L.2–L.3	L.3	—	—				
R.H.	m	28	L. L.2–L.3	L.3	—					
Four-Quarter										
D.CR.	f	46	L. L.2–L.3	L.3	—	—				
			R. L.2–L.3	L.3+	—	—				
B.E.	f	33	L. L.2–L.3–L.4	L.3+	—	—				
			R. L.2–L.3–L.4	L.3+	—	—				
C.D.	f	52	L. L.2–L.3	L.3+	—	—	—	—	+	—
			R. L.2–L.3	L.3	—	—	+	—D	+	—
A.D.	f	29	L. L.2–L.3	L.3	—	—			—	—
			R. L.1–L.2–L.3	L.3	—	—				
A.A.	m	29	L. L.2–L.3	L.3+	—	—				
			R. L.2–L.3	L.3+	—					
17 sides			Sympathetic activity	Present	0	0	1	0	2	0
				Absent	17	17	1	2	1	3
				Totals	17	17	2	2	3	3

(C.D.—right) which early showed in complete resection of vasomotor pathways. If all transthoracic cases are removed as well as this last-mentioned side, and also the case of imperfect retro-pleural thoraco-lumbar resection, after 3 months sympathetic activity in the *feet* was found to be as follows:

	Present	*Absent*	*Eventual recovery (approx.)*
Sudomotor activity (on foot)	—	57 sides	never
Vasomotor activity (in toe)			
Blood flow .	8 sides	16 sides	30 per cent.
Pulse wave .	5 sides	19 sides	20 per cent.

If the 1st and 2nd thoracic ganglia were removed:

	Present	Absent
Sudomotor activity (on hand)—early .	1 side (?2)	13 sides
Vasomotor activity (in finger)—early		
Blood flow .	7 sides	9 sides
Pulse wave .	4 sides	10 sides

Five sides showed a decrease in blood flow in the finger after heating the patient.

After an interval of three months or longer, however, sudomotor and vasomotor activity in the hand was as follows:

	Present	Absent	Eventual recovery per cent. (approx.)
Sudomotor activity (on hand)—late	10 sides	1 side (? recovering)	90
Vasomotor activity (in finger)—late			
Blood flow .	12 sides	1 side	92
Pulse wave .	7 sides (?8)	2 sides	78

The contrast in eventual recovery of sudomotor activity in the upper and lower limbs may now be summarized as follows:

	Present (sides)	Absent (sides)	Probable eventual recovery
Hands (excluding all incomplete resections)	10	1?	nearly always
Feet	4	62	very rarely
Feet (excluding all incomplete resections)	—	57	never

SUMMARY

After cervico-dorsal sympathectomy—which includes the stellate and 2nd thoracic ganglion—and thoraco-lumbar sympathectomy—which includes the 4th thoracic to the 3rd lumbar ganglion—sudomotor activity in the skin is retained in:

the central area of the face;

the escape area—comprising at least the first and second lumbar dermatomes;

the perineum.

Elsewhere the skin is anhidrotic, as would be expected from a know-

A similar summary of the findings after cervico-dorsal sympathectomy is shown in Table III. This includes five cases on whom four-quarter sympathectomy was performed. It will be seen that the lower level of the anhidrotic area is rather variable, though resection of the stellate and T.2 ganglia ensures a more constant pattern which usually includes the T.1 dermatome. (T.1 + indicates a tendency to extend lower on the thorax.)

When these cases were examined soon after operation, sudomotor activity was present in the central mask of the face in all cases (18 sides), and was present around the external auditory meatus and over the larynx less constantly. The occurence of sweating retained in these areas was as follows:

	Present	*Absent*	*Retained activity per cent. (approx.)*
Central mask of face .	18 sides	never	always
Skin around ear . .	7 sides (?9)	9 sides	50
Skin over larynx . .	10 sides (?14)	4 sides	70

In one case (A.D.), when first examined more than 18 months after operation, sudomotor activity had completely recovered on one side of the face, but localized sweating on the central face and over the larynx was still present on the other side.

It is possible, however, that these 4 sides would have shown sweating if it had been searched for, but the 2 cases concerned were among the first to be tested.

Horner's syndrome was produced in all cases which had undergone resection of the stellate ganglion, but at subsequent examinations it was no longer detectable in all but 2 (out of 12 sides) when it was much diminished in degree. All patients eventually had some recovery of sympathetic activity in the eye, but it was complete only in 83 per cent. (approx.).

Sudomotor activity in the hand shortly after operation was not evident except on one side when only part of the stellate and middle cervical ganglia were resected, and one case of T.2 and T.3 ganglionectomy in which it was present on 1 side and partially present on the other. At subsequent examinations at intervals greater than three months after operation, sudomotor activity had recovered on every hand examined although it had been shown to have been absent here initially. The one exception was first examined at four months after operation but sweating had started to appear on the front of the upper arm. Vasomotor observations on this side also suggested early recovery.

Part Two

AUTONOMIC PATHWAYS TO SPECIAL AREAS

ledge of the generally accepted anatomy of the sympathetic nervous system.

The area of anhidrosis resulting from lumbar or thoraco-lumbar sympathectomy is permanent: that after cervico-dorsal sympathectomy invariably recovers at least a moderate degree of sympathetic activity within several months.

The explanation for the retained activity in the escape area is via alternative sympathetic pathways passing through the lumbar intermediate sympathetic ganglia. An account of these is given in Part Two, and possible explanations for the sudomotor activity to the facial and perineal areas will also be discussed there.

Chapter 7

EXPLANATION OF SWEATING IN THE 'ESCAPE' AREA—INTERMEDIATE GANGLIA

THE observations made on these cases of thoraco-lumbar and lumbar sympathectomy are summarized in Tables I and II. It will be seen that there is a constant escape area, which still shows thermoregulatory sweating, present in all cases. This escape area obviously has a segmental pattern and always comprises the dermatomes L.1 and L.2 and often T.12 and L.3, but may include T.11 or T.10 as well, on one or other side, for the upper border is markedly asymmetrical and irregular. The lower border does not extend to the usually accepted lower level of the L.3 dermatome in seven cases (9 out of 63 sides), but one of these cases was subsequently shown to have a prefixed type of lumbar plexus.

The upper border of the anhidrotic area shows fairly close agreement with the lower border of the dermatome which is supplied by that nerve root next above the intended upper level of resection of the paravertebral sympathetic chain.

All these patterns agree fairly closely with those shown by Ray and Console (1948 and 1949) which are the only other detailed ones yet published. In general, those patterns illustrated here (Figs. 1–19) are more variable and asymmetrical with their various 'islands' and 'peninsulas' but the author believes that these irregularities have an anatomical basis. Recent observations by Wilson (1950) on similar cases, which were tested by the quinizarin chemical method, show the persistence of sweating in the escape area; in one or two of his cases this appears to extend upwards even to a higher level than it does in this series.

Other observations on eleven cases after thoraco-lumbar sympathectomy tested for thermoregulatory sweating by the starch-iodine method by Palumbo *et al.* (1950) also show patterns in general agreement with those of Ray and Console.

Richter and Woodruff (1945) described a series of patients who had undergone lumbar paravertebral sympathectomy but in which the extent of the resection had been carried to different levels. Many of the patterns they obtained show similarities in regard to the lower level of the escape area. When, however, the pattern did not correspond to the intended level of resection, these observers assumed that the surgeon had mistaken the level of resection and had removed a lower segment



local anaesthetic in the lumbar region (e.g. Case R.R.), it has been apparent to the author that even small volumes of fluid do not remain precisely localized but diffuse up and down in the psoas sheath and will produce a sudomotor block at other levels than at the one at which the injection was given. In this case, therefore, the injection given at the level of T.12 may have diffused into the upper edge of the psoas sheath to affect the L.1 segment or, owing to the obliquity of the needle, may have been directed at that level initially. The 2nd lumbar segment of the chain—or at least the white rami communicantes from the 2nd lumbar nerve root, which ordinarily comprise the lowest level of the sympathetic outflow—do not appear to have been totally blocked by the injection, since sudomotor function persists in part of the sacral dermatomes, and the preganglionic fibres to the corresponding sacral ganglia must therefore be intact. There is a belt of anhidrosis on the right side which extends over the upper buttock around onto the lateral aspect of the upper thigh. This belt is made up in part from the T.12, L.1 and L.2 dermatomes, and comprises more of the posterior primary divisions than the anterior. The striking observation, however, is that anhidrosis has been produced in at least part of the escape area as compared with the opposite side and with all other cases. There is also an area of anhidrosis on the lower buttock and posterior part of the inside of the thigh, so presumably some of the preganglionic fibres to the 2nd and 3rd sacral ganglia were involved in the injection. The paravertebral sympathetic ganglia between T.7 and T.11 segments, however, do not appear to have been affected by the injection, though the intention had been to block most of the origins of the splanchnic nerves.

This observation that paravertebral injection of phenol will produce absolute anhidrosis in part of L.1, L.2 dermatomes has been confirmed in other cases. These are not illustrated, but they conform to the general but irregular pattern of the Case S.W. Similarly, Ray and Console (1948) and Cone (1950—unpublished) have confirmed that section of the anterior nerve roots T.12, L.1 and L.2 will prevent the sweating activity on the anterior thigh. Such a procedure usually results in weakness and distension of the lower abdominal wall and therefore cannot be recommended.

The inference gained from these cases was that there must be sympathetic pathways and probably ganglia lying inside the psoas sheath which did not necessarily receive preganglionic fibres from the paravertebral sympathetic chain, though they did from the nearby spinal nerve roots. On the right side, not only had the sudomotor supply from the ganglia in the true paravertebral sympathetic chain been affected by the injection, but these other ganglia, which send part of their sympathetic supply to the same area of skin, had also been deprived of either their preganglionic or postganglionic connections.

*of chain than the one stated. As they did not realize that the inter*mediate ganglia were still supplying the area on the front of the thigh and inside of the knee, they endeavoured to fit their observations into different dermatome patterns. Their conclusions in this respect must be fallacious.

Ratcliffe and Jepson (1950) have reported a series of cases in which they also examined the sweating patterns by the electrical skin-resistance method after lumbar ganglionectomies. They did not heat their patients, however, and it would therefore appear that it is for this reason that their patterns are not comparable to those described here.

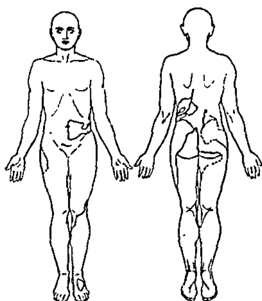


FIG. 29. Case S.W. Paravertebral phenol injection.

CASE S.W. (Fig. 29). This pattern is of particular interest, since it was from this case that the author obtained the clue for the true explanation of the origin of the alternative sympathetic pathways to the escape area.

At operation the left paravertebral sympathetic chain was resected between T.8 and L.3 segments inclusive, and on examination 4½ months later, the upper border of the anhidrotic area reaches the level of T.9 with a 'peninsula' extending below this, around each side. The upper border of the escape area is at the upper level of the L.1 dermatome as usual, and the lower border extends into L.3. There is a small area of low electrical skin resistance on the dorsum of the left foot, which coincided with marked pitting oedema in this situation, and is therefore probably due to factors affecting the resistance of the skin other than thermoregulatory sweating.

On the right side paravertebral injections of phenol (5 per cent.) were made at the level of the spinous processes of the 7th to 12th thoracic vertebrae. In this technique a needle is introduced 6 cm. from the mid-line behind, and directed forwards and medially until it just grazes off the edge of the antero-lateral aspect of the body of the vertebra: the tip should then be lying in the position of the paravertebral sympathetic chain.

From observations on other patients who have had such injections of

ate' ganglia are always present in the nerve roots at these levels—and, indeed, may nearly always be found in relation to all lumbar ganglia (Figs. 30 and 31). The ganglia are invariably present in relation to the L.1 and L.2 nerve roots, but are only rarely to be found in relation to the T.12 nerve roots (or higher) and the S.1 root (or lower). The ganglia are of varying size and distribution along the course of both the 'grey' and the 'white' rami communicantes, but are rather more common along the former, which lie more transversely and at a deeper level close to lumbar arteries, than are the latter, which are more superficial and more oblique. The ganglia are frequently multiple and may be seen at any point along the course of the rami, either close to the paravertebral sympathetic chain, in an intermediate position, or close to the lumbar nerve: indeed, they are sometimes even buried in the anterior primary division and have also been seen on the posterior primary division (Fig. 30). Intermediate sympathetic ganglia have also been described in relation to the cervical and upper thoracic nerve roots by Wrete (1934*a* and *b*), Skoog (1947) and Ehrlich (1949), and their presence here confirmed by the author.

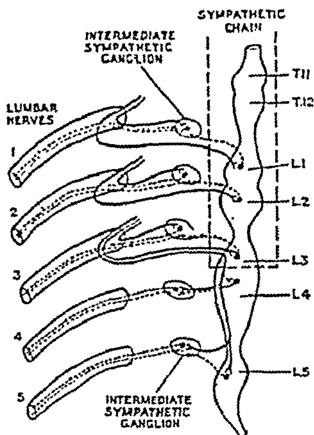


Fig. 32. Diagram to show the effect of thoraco-lumbar sympathectomy on connections of intermediate ganglia. Preganglionic fibres indicated as continuous lines, post-ganglionic fibres as interrupted lines. The rectangle indicates the tissue removed in the sympathectomies. Preganglionic fibres in this instance are shown in the third lumbar root. Boyd, J. D. and Monro, P. A. G. (1949). *Lancet*.

It will be apparent, therefore, that such ganglia would still be able to supply sudomotor fibres to the skin, even though the paravertebral sympathetic chain has been resected. If, however, the lower level of the thoraco-lumbar outflow does not extend below L.2 nerve root, those intermediate ganglia associated with L.3, L.4 and L.5 nerve roots would be deprived of their preganglionic fibres, which ordinarily must reach them through the paravertebral sympathetic chain (Fig. 32).

The alternative autonomic pathway to the escape areas (T.12–L.3) is therefore easily and obviously explained by the presence of the lumbar intermediate ganglia which lie in relation to the appropriate nerve roots T.12–L.3. It must be realized, however, that it may not be necessary for these ganglia to lie outside the range of the L.1 and L.2 nerve roots, since it may be possible that a ganglion in relation to the L.1

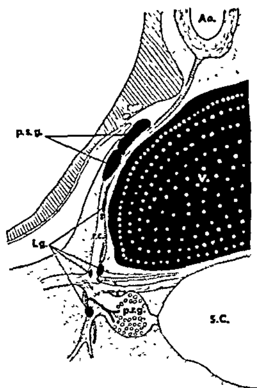


FIG. 30. T.S. 100 mm. *c.r.* human foetus. Camera lucida drawing at level of second lumbar vertebra, left side. Showing four intermediate ganglia in relation to ramus communicans and one in relation to posterior primary division of nerve root. Boyd, J D. (1957) *Brit. med. Bull.*

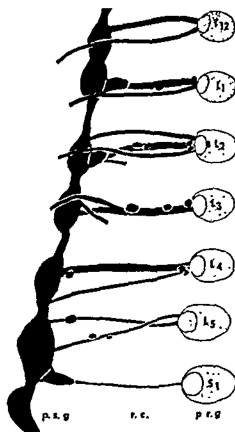


FIG. 31. Diagram of lateral view of left side of a 100-mm. *c.r.* human foetus showing position of lumbar intermediate sympathetic ganglia along rami communicantes. By permission of J. D. Boyd.

p.s.g. paravertebral sympathetic ganglia
p.r.g. posterior root ganglia
i.g. intermediate ganglia
r.c. ramus communicans
Ao. aorta
s c. spinal cord in spinal canal

nerve root may be able to supply most of the T.12 dermatome by overlap, and similarly a ganglion in relation to L.2 nerve root could supply most of the L.3 dermatome. The only essentially constant features of this alternative pathway must be preganglionic fibres, ganglion cells and postganglionic fibres in relation only to the 1st and 2nd lumbar nerve roots.

Observations on human embryos have shown that small 'intermedi-

have been able to function in a similar manner. In both instances the visceral fibres would have been sectioned.

The intermediate ganglia supplying the escape area—which are shown in Fig. 33(*c*)—will still function normally after paravertebral sympathectomy, since both their preganglionic and postganglionic fibres will be intact. Their visceral fibres would be divided by a para-

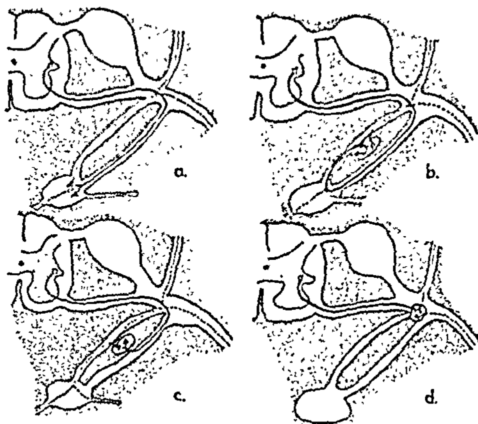


Fig. 33. Possible sympathetic pathways.

a. Paravertebral ganglion only.
b. Intermediate ganglion supplied by preganglionic fibre via the paravertebral ganglion.
c. Intermediate ganglion supplied by preganglionic fibre directly from nerve root.
d. Intermediate ganglion on or in anterior primary division.

Preganglionic fibre shown as a continuous line, postganglionic fibres shown as dotted lines. Boyd, J. D. (1957) *Brit. med. Bull.*

vertebral sympathectomy at this level. When the intermediate ganglia are actually in or on the nerve roots themselves—as in Fig. 33(*d*)—then they are even more likely to survive paravertebral sympathectomy and are very inaccessible to the surgeon.

For several months after thoraco-lumbar sympathectomy patients have a marked postural hypotension, and shortly after operation they are apt to faint if they stand up suddenly.

Although no special observations have been made in regard to vasomotor fibres from the lumbar intermediate sympathetic ganglia, no

Sweating, therefore, should not be expected below the lower edge of the L.3 dermatome. Complete anhidrosis below L.3 is found to be the rule. In certain instances (20 sides—marked L.3+ in Tables I and II), however, it might be considered that sweating extends so far down the leg that it is present at a lower level than the usual L.3 dermatome. It is possible that in these cases the L.3 nerve roots may either receive post-ganglionic fibres from the intermediate ganglia in relation to L.2 root via the interconnecting loops connecting these ganglia, which are described later and have also been reported by Kuntz (1949) and Alexander (1949) and Kuntz and Alexander (1950), or that in about one-third of all cases there may be preganglionic fibres also in the L.3 nerve root below the usual lower level of outflow, and these fibres may supply intermediate ganglia at this level. Sheehan (1941) found fine myelinated 'preganglionic' fibres at this level in only one side in 18.

Sheehan (1941) does not correlate the lower level of the sympathetic outflow with the incidence of pre-fixed or post-fixed lumbar plexus in man, but he states that a post-fixed plexus was present on 25 per cent. of the sides he examined in the monkey. It is interesting to associate this figure with the occurrence of sweating extending down into the L.3+ dermatome in man—20 out of 63 sides, or 32 per cent.

It is with this possibility in mind that preganglionic fibres are shown leaving L.3 anterior nerve root in Fig. 32. Only in one case did sweating appear in the true L.4 dermatome (Case W.T.).

The lower thoracic nerve roots inconstantly have associated intermediate sympathetic ganglia, and if they do they are not necessarily present on both sides at the same level. Such irregular occurrence will explain the commonly found irregular and asymmetrical upper border to the escape area. It is possible, however, that in certain cases this may be due to a portion of the sympathetic chain being left intact at operation as it passes through the diaphragm. This was shown to be the case in Case S.S.

Fig. 33(*a*) shows the generally accepted arrangement of the preganglionic (continuous line) and postganglionic (interrupted line) fibres to the paravertebral sympathetic chain. Note that the postganglionic fibres in the 'grey' ramus join the nerve root proximal to the site where the preganglionic fibres leave it in the 'white' ramus. After a paravertebral sympathectomy both the peripheral and visceral fibres should degenerate.

The slight change in the pattern of the anhidrotic area on the thorax after the injection of carbachol may be explained by intermediate ganglia whose preganglionic fibres reaches them after having first passed through the paravertebral chain. Such ganglia are illustrated in Fig. 33(*b*). It is also possible that if the paravertebral ganglion was incompletely removed, some cells in the paravertebral ganglion might

etc.). The possibility that some of the posterior dermatomes cross the mid-line has been discussed in relation to Case J.T. (p. 44).

CONCLUSIONS

It appears that after thoraco-lumbar paravertebral sympathectomy a sudomotor escape area constantly persists in the dermatomes T.12–L.3. Such an area will be supplied by the lumbar intermediate sympathetic ganglia associated with the L.1 and L.2 nerve roots whose preganglionic and peripheral postganglionic connections will have remained intact after paravertebral sympathectomy. If intermediate sympathetic ganglia are present above these levels, then the escape area will be correspondingly raised on this side. The intermediate sympathetic ganglia associated with the lower lumbar nerve roots (L.4 and L.5) will not ordinarily cause sweating below the L.3 dermatome, since their preganglionic fibres will have been sectioned below the lower level of the sympathetic outflow (L.2 or L.3). In this respect they are similar to the paravertebral ganglia at these levels.

Sweating also persists around the perineum, and on rare occasions may be induced, after the injection of carbachol, in the mid-line of the body, though no satisfactory explanation for the latter can yet be made.

evidence has been found that the sudomotor and vasomotor fibres from these ganglia are distributed to different areas of skin. One striking example of the close association of such innervation was made on a patient who stood up to be photographed after the lines marking the borders of the typical anhidrotic and escape areas had been drawn on his skin.

The patient (E.I.) stood for as long as he could in the glare of the lights while the photographers were making ready, and it was quite obvious that the skin of the escape area and the normal non-denervated skin were pale due to the actively constricted vessels, whereas the thoracic anhidrotic area and the anhidrotic area on the legs below the knee were quite livid in colour, since not only were the vessels here dilated, but also were full of stagnant blood which was becoming cyanosed. The lines marking the sweating area accentuated the contrast in colour. Unfortunately the photograph was not taken before the patient began to feel faint, and on a later occasion, when another attempt was made, the contrast in colour was not so great. Infra-red photographs do not show the distinction very definitely, though the superficial veins are well seen.

Ray and Console (1948) have reported that they made observations of the skin temperature in different areas of the body and found that it remained consistently higher in the anhidrotic areas, but was lower and more variable in the normal skin and in the escape area. The author has made similar measurements which confirm their observations.

Certain aspects of pilomotor function were discussed in Chapter 5 in regard to dermatographia. No attempts, however, have been made to produce a general pilomotor reflex such as by ice or cold douching. It has been noted that 'gooseflesh' appears on the lower abdomen in the escape area if the patient is cooled too quickly after heating, but no precise observations have been made as to whether or not this can occur in the anhidrotic areas other than when it is locally excited.

Besides the escape area on the lower trunk and thighs, low electrical skin resistance was also noted in the perineum and in the S.4 and lower dermatomes. This area, of course, lies in an area made up of deep folds of the skin and, in the front of the groin, it adjoins the escape area and is usually continuous with it behind in the natal cleft. The implications of sweating in this area are discussed fully in Chapter 10.

The occasional occurrence of sweating in the mid-line of the body, such as is produced by carbachol, cannot as yet be explained other than by the suggestions made in the previous chapter, but it is not common and may be in some way related to the median fusion line of the body. Attempts have not yet been made to produce a high resistance in this area by blocking or sectioning the segmental nerves on each side of the mid-line, but such an experiment will be kept in mind in case a convenient opportunity presents itself (subsequent to abdominal operation,

Echidna aculeata (spiny anteater), *Ornithorhynchus paradoxus* (platypus), *Erinaceus europaeus* (hedgehog), *Cynocephalus hamadryas* (flying lemur) and *Dama vulgaris* (fallow deer)—thoracic region.

No particular name was given to these ganglia, however, until Hirt (1921) described them in the rami communicantes of the lumbar region in *Lacerta agilis* (lizard) and *Varanus niloticus* (monitor lizard). He gave the name 'intermediate' for them, on account of their position. Hirt's paper is, of course, written in German and he uses the adjective 'intermediäres'.

The first mention of these ganglia in a textbook appears to be by Wertheimer and Bonniot (1926), but they described them only as 'pseudoganglia' on the rami communicantes. In the next year Hovelacque (1927) also mentions them, and states that they lay usually beneath the osteofibrous ring of the psoas muscle, but he thought that they were very rare.

In a long paper in Italian by Rossi (1930) on the development of the abdominal and pelvic sympathetic, he gives an account of these ganglia and discusses their position and variability in the lumbar region of the human embryo up to 100 mm. Rossi was familiar with the accounts of Marinesco and Minea, and of Hovelacque.

Gruss (1932) followed this with an account of macroscopic ganglia on the rami communicantes in the lumbar region in human foetuses, infants and adults. He only once noticed them in the cervical region: he also included a report on their presence in the dog. He illustrates his paper with excellent microphotographs of ganglia impregnated with silver by the Bielschowsky-Gros technique, which show that the ganglia contain undoubtedly multipolar sympathetic ganglion cells.

Delmas and Laux (1933) in their textbook of surgical anatomy of the sympathetic nervous system mention that ganglion cells are present on the lumbar nerve roots at the site of a ramus communicans (*page 75*).

In 1934 (*a* and *b*), Wrete published the first of his papers on the intermediate ganglia in the human embryo. He examined twelve transversely, and serially sectioned human embryos measuring 10–77 mm. *c.r.* In this account he describes the presence of these small ganglia on the rami communicantes in the cervical and upper thoracic region, and he follows Hirt in using the adjective 'intermediate' to describe them. In the following year (1935) he gives a fuller account of their presence and development in all regions of the body. He found that they were consistently present only in the cervical, upper thoracic and lumbar regions, but that they were asymmetrical and variable.

Orloff (1937) describes the presence of ganglia along the rami communicantes in 36 out of 100 adult dissections which he examined. He considered that the high incidence of these ganglia might be the cause of failure after ramisectomy or lumbar ganglionectomy.

Chapter 8

INTERMEDIATE SYMPATHETIC GANGLIA— HISTORICAL INTRODUCTION

Although sympathetic ganglia along the course of the rami communicantes had not been reported in the English language until 1946 and 1947, continental anatomists have made reports of their presence during the past century. Some of the more recent workers had suggested that the presence of these ganglia might invalidate the purpose of operations for paravertebral sympathectomy, but none had made investigations to see if this were true.

Cruveilhier (1845 and 1852), according to Villemin and Dufour (1930), appears to have been the first to notice the presence of these ganglia, when he described small nodules on the course of the rami communicantes. He found that sometimes these ganglia were connected to the nerve root and to the sympathetic chain by several separate rami.

In the 5th edition (1877—see footnote, *page 721* of Vol. 3) of Cruveilhier's treatise of descriptive anatomy, reference is made to the ganglia on the rami communicantes in the following paragraph:

> Une disposition fort remarquable des rameaux de communication entre les paires et les ganglions lombaires, c'est la présence de ganglions ou renflements sur le trajet de ces rameaux, et ce qui n'est pas moins remarquable, c'est le nombre presque indéfini d'anomalies qui existent à ce sujet. J'ai trouvé jusqu'à trois renflements ganglionnaires sur le même rameau. Quelquefois deux ou trois rameaux de communication, parvenus sur le côté de la vertèbre, convergent vers un petit ganglion anormal, duquel deux ou trois rameaux qui vont au ganglion lombaire correspondant. . . .

There can therefore be no doubt that the 'ganglionic swellings' seen by him were indeed the lumbar intermediate sympathetic ganglia.

Later, Onodi (1886) reported the presence of ganglia in the rami communicantes of human embryos. Following this there was another long interval until 1908, when Marinesco and Minea gave the first detailed account of the presence of these small ganglia in adult man. They regarded them as definitely sympathetic ganglia and stated that they lay beside the spinal nerves and were usually attached to the rami communicantes.

In the same year van der Broek (1908) reported microscopic ganglia in the rami communicantes of lumbar regions of various animals:

cervical and lower lumbar regions, and in the former quite small, but in the latter attaining the size of and sometimes replacing the segmental ganglion of the chain.' It should be noted, however, that Pick and Sheehan were using a similar technique to that of Wrete: they dissected their human adult cadavers and foetuses under a lens, subsequently removed the rami and ganglia, etc., labelled them, stained them in bulk with osmic acid, and sectioned them in paraffin. It is possible, therefore, that they might have missed the smaller ganglia in relation to the upper lumbar nerve roots. Pick and Sheehan realized, however, that these ganglia would be left intact after the usual type of lumbar sympathectomy.

Skoog (1947), who was then working in Wrete's department, has given the first account of the intermediate ganglia in the cervical region in the adult: writing in English, he uses the adjective 'intermediate' to describe them. He dissected the brachial and cervical plexi on both sides in five subjects, but sectioned only the nerves, rami and ganglia on one side in each. The ganglia were variable in position—sometimes very close to the spinal nerve—but were generally present on the communicating rami to all the cervical nerves and also the 1st thoracic nerve: in one case ganglia were present on the ramus to the 2nd thoracic nerve. The number of ganglia varied between ten and nineteen on one side, but only some were visible to the naked eye. He suggested that these ganglia might be the explanation for the relapse following cervicodorsal sympathectomy, since he realized that a sympathetic pathway might exist here which lay entirely within the spinal system.

In 1949 Boyd and Monro published their paper, in which they suggested that the partial retention of autonomic function, which still occurred on the lower trunk and the front part of the thighs in patients who had undergone thoraco-lumbar sympathectomy, was to be explained by the presence of alternative sympathetic pathways, whose cell stations lay in the intermediate ganglia of the lumbar region. Although the author had previously read the papers of Pick and Sheehan and of Skoog, the presence and great variability of these ganglia in the lumbar region was confirmed in the numerous human embryos and foetuses in Professor Boyd's collection. In an addendum to their paper, the presence of these ganglia was reported in two nerve roots already examined in a patient of this series.

A few months earlier, but unknown to the author, Alexander (1949), Kuntz (1949), Henderson (1949) and Ehrlich (1949), working together, had published a series of papers—written individually, and collectively (1949)—on the presence of 'inconstant sympathetic ganglia' located in relation to the 1st and 2nd thoracic and the 1st, 2nd and 3rd lumbar nerves. They also reported the presence of anastomotic loops of autonomic fibres, not only between the 1st and 2nd thoracic nerves and

The following year Fagarasanu (1938), in a series of papers on the variations in the topographical anatomy of the lumbar sympathetic chain, gave an account of the presence of macroscopic ganglia which had 'deviated' (*Fr.* = *déviés*) from the chain in human foetuses and adults. He found that these ganglia were always covered by the psoas muscle and nearly always obscured by the lumbar artery. They were present along the rami communicantes in 34 per cent. of his 76 cases, and as outgrowths from the paravertebral chain in 16 per cent., making a total incidence of 50 per cent. of all cases. He noticed that these ganglia were often to be found along the lumbar artery, and often sent one or two rami around it. He was familiar with the accounts of the other workers which were published in French, such as Hovelacque, Wertheimer and Bonniot, Delmas and Laux and Orloff, but did not appear to be aware of those of Marinesco and Minea, Gruss and Wrete.

Wrete (1941) continued his researches on the presence of the intermediate ganglia in laboratory animals such as the mouse, rabbit, cat, white rat and monkey (1951). He found that they were totally absent in the embryos and young of the mouse, and rare in the cervical region and variable in the lumbar region of the rabbit. They were present in the lumbar and sacral region of the cat, but in the white rat they were much more common, especially in the cervical and upper thoracic, and lumbar and sacral regions: in this respect they were similar to man. He forecast that these ganglia in animals would vitiate much experimental work on the sympathetic nerves unless their presence was taken into consideration.

Two years later (1943) he followed this with a further account of these ganglia in the lumbar region of a transversely sectioned and silver-impregnated human embryo of 81 mm., and also in the same region of four human adults. These he dissected with a hand lens on one side only, and removed the rami communicantes, the ganglia and spinal nerve roots, all of which he sectioned longitudinally. Although by this technique he found as many as fourteen ganglia present on one side in one specimen, in another he could find only two. He did, however, find intermediate ganglia present in every specimen, as compared with Fagarasanu who could find them in only 50 per cent. of his specimens; Wrete does not appear to have been acquainted with Fagarasanu's work.

Pick and Sheehan (1946), in their account of the sympathetic rami in man, mention 'intermediary' ganglia along the course of the rami. They were familiar with both Wrete's and Fagarasanu's papers and presumably translated the German 'intermediäres' as 'intermediary' instead of 'intermediate', for Fagarasanu and other workers writing in French make no attempt at terminology. Pick and Sheehan state that these ganglia were 'surprisingly common' and nearly always present. Pick and Sheehan continue: 'They were most frequently found in the

the interconnecting autonomic nerve loops between certain nerve roots. Further observations include the presence of similar fine nerves which extend along with the lumbar segmental arteries towards the sympathetic ganglia on the sides of the aorta and have thus escaped the operation of sympathectomy.

the 2nd and 3rd—which had earlier been reported by Kuntz (1927) and Kirgis and Kuntz (1942)—but that these loops also extended as low as the 4th thoracic nerve. The interconnecting rami associated with ganglion cells located in relation to spinal nerve roots occurred again in the lumbar region between the 12th thoracic and 3rd lumbar nerves.

Most of the above observations, with the exception of the interconnecting rami in the lumbar region, had already been made by Wrete, who in his illustrations (1943) also shows such an anastomotic loop between the 2nd and 3rd lumbar nerves. Wrete has also described such anastomotic loops between the cervical nerve roots, for which Skoog (1947) used the term 'rami communicantes grisei bipartiti of Wrete'. Alexander *et al.*, however, describe the presence of sympathetic ganglion cells not only adjacent to the nerve roots at the site of the grey and white rami, but also embedded in the central nerve roots themselves. They also realized that these ganglia would not be interrupted by ordinary paravertebral sympathectomy. Henderson (1949) has also given a fuller account of the occurrence of these ganglia, which had first been observed by Gruss in the lumbar region of the dog. In the following year he assisted in an interesting account (Randall, Alexander, Hertzman, Cox and Henderson, 1950) of an experimental verification of the autonomic function of these ganglia in the dog. After a complete lumbar paravertebral sympathectomy, vasoconstrictor and sudomotor activity was observed to return in the hind limb, and *post mortem* the presence of sympathetic ganglia was confirmed in relation to the relevant nerve roots.

In the meanwhile Monro (1950*a*) had given an account of the presence of intermediate sympathetic ganglia in relation to the upper four lumbar nerves of a patient who previously, following thoraco-lumbar sympathectomy, exhibited a retention of sudomotor activity in the appropriate areas. Degeneration of the majority of cells in certain ganglia in relation to the 1st and 2nd lumbar nerve roots suggested that these cells had sent their postganglionic fibres towards the viscera, and thus they had been damaged by the sympathectomy.

Following these observations, another report (Monro, 1950*b*) was made in regard to sympathetic pathways after sympathectomy in the lumbar and in the cervico-dorsal regions, and their innervation was discussed in relationship with the intermediate ganglia of these regions. More recently (Monro, 1951*a*) a further account has been made of the connections of the intermediate ganglia in relation to the upper four lumbar nerves on the other side of the same specimen which had been described earlier. The presence of many and variable intermediate ganglia in relation to the grey and white rami and on, in and around the anterior primary divisions of the upper four lumbar nerve roots has been confirmed, as also has been the contribution of some of them to

roots. Care was taken to preserve the rami communicantes and the remains of the sympathetic chain; this, as had been intended, was found to have been resected down to the level of the lower border of the 3rd lumbar vertebra on either side. The anterior portion of the psoas was dissected away to expose the nerve roots back to the intervertebral foramen in the hope of distinguishing macroscopic intermediate sympathetic ganglia in relation to the lumbar nerves or their rami. It was apparent that a prefixed lumbar plexus was present in this case, since the 1st lumbar nerve root contributed to the femoral and obturator nerves. No definite ganglia were recognized, but several suspicious nodules were subsequently found to consist only of fat! As the whereabouts of the intermediate ganglia was unknown, no attempt was made to dissect the nerves clean for fear of damaging the ganglia. Accordingly the specimen was labelled and photographed for reference. The whole block was then fixed in 10 per cent. formalin after the spinal cord had first been removed and placed in alcohol.

After fixation, each nerve root with its sensory ganglion and rami communicantes was dissected away from the intervertebral foramen forwards towards the site of the scar tissue resulting from the paravertebral sympathectomy.

No attempt was made to clean the nerves or their rami, which were therefore included in a small block of tissue in which was also incorporated the corresponding lumbar arteries, veins and surrounding fat. Each nerve root T.12–L.5, obtained in this way, was photographed for reference, and also all arranged together as they were in the body (Fig. 45). In this photograph they are shown as seen from the antero-lateral side with the posterior root ganglia and the peripheral nerves on the left and the rami extending towards the scar tissue on the right.

The nerve roots were then embedded individually in paraffin, and flattened during the process, so that the long axes of the anterior primary division and the rami communicantes lay in the same plane. The sections were cut serially in this plane, mostly at 15 μ from behind forwards. Later the lower end of the paravertebral sympathetic chain corresponding to the ganglia on this side in relation to the 4th and 5th lumbar vertebrae was also removed in a similar manner and sectioned longitudinally in the plane of the rami. The 9th thoracic nerve root, which was that next below the intended upper level of resection of the paravertebral chain on this side, was treated somewhat differently. No attempt was made to dissect the nerve root or its rami. They were excised entire in a block of tissue extending from the vertebral canal behind, through the intervertebral foramen, close to the periosteum over the transverse process and head and neck of the rib, and of the body of the vertebra and the fibrous tissue of the intervertebral disc, forwards to the pleura and the scar tissue of the sympathectomy. This block of tissue was im-

Chapter 9

§1A. THE LUMBAR INTERMEDIATE GANGLIA—RIGHT SIDE

THE patient whose sweating pattern (*Case s.s.*) is shown in Fig. 4 (bottom left) and in Fig. 34, subsequently returned to the hospital and died of uraemia fifteen weeks after the operation on the right side and ten weeks after that on the left. A post-mortem examination was performed within eighteen hours of death. The associated pathology was consistent with a diagnosis of malignant hypertension.

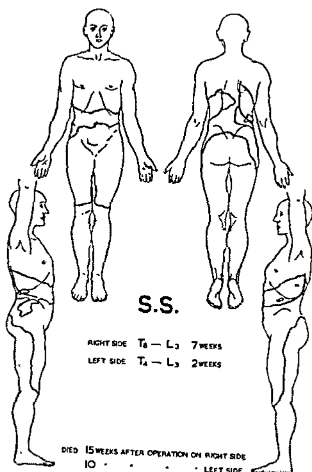


FIG. 34. Case S S. Thermoregulatory sweating pattern Post-mortem examination was performed subsequently on this case.

An immediate preliminary examination of the right lumbar region was made by Professor Boyd and the author.

METHOD

After removal of the viscera and skin, the ribs were cut through along a line about two inches on either side of the vertebrae. The sacro-iliac joints were cut through with a saw on either side, and a block of tissue containing the vertebral column from the level of the upper border of the 8th thoracic vertebra and including the sacrum and coccyx was removed in one piece together with the adjacent muscles and nerves.

The psoas muscle was split in the plane of the emerging lumbar nerves which were traced back through it to their origins from the nerve



Fig. 35. First lumbar nerve root (right side). No. 8 ganglion. Some cells are normal but others are 'degenerate'. H and E $\times$ 180.

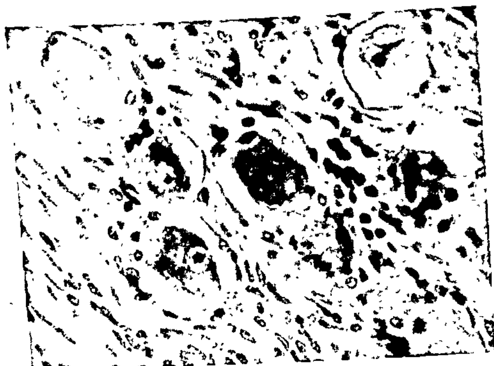


Fig. 36. Cells in 5th lumbar paravertebral ganglion. H and E $\times$ 500.

pregnated with silver and sectioned in a similar manner to the others, but with the intention of revealing all the fine nerve connections to this nerve root and possible evidence of nerve regeneration.

The sections of the nerve roots and the paravertebral ganglia were stained in rotation by a variety of techniques which included haematoxylin and eosin, Masson's trichrome, Nissl's thionin, iron haematoxylin and a modified Bielschowsky. Transparent scale models were prepared from projection drawings of the nerve elements in the sections of the 1st and 2nd lumbar nerve roots and rami. These give an excellent idea of the sites and connections of the intermediate ganglia (Figs. 40 and 43). A more complete account of this work, with photographs of relevant ganglia and their connecting rami, has been given by Monro (1951*c*).

FINDINGS

9TH THORACIC NERVE ROOT

This root had been impregnated with silver in the block. There was no evidence of any regeneration of the paravertebral sympathetic chain downwards from the cut upper end. Similarly, there was no evidence of a regenerated greater splanchnic nerve from the nerve root at this level nor from higher thoracic nerve roots. A fine bundle of intact nerve fibres could be traced from the nerve root towards the intercostal artery, and a branch of this nerve accompanied the artery back towards the aorta: this fine branch had escaped section at the time of the operation since it lay deep to the vessels, between them and the body of the 9th thoracic vertebra. It is not possible to say if it contained autonomic or only sensory fibres, since both may be fine and with but little myelin. It was very similar to other fine nerves seen to accompany the lumbar arteries on the left side. These nerves were seen to supply the arteries by finer twigs at intervals, and could be followed across beneath the side of paravertebral resection towards the aorta where they joined the sympathetic ganglion tissue in this situation: they will be discussed again later.

Interwoven between the scar tissue at the site of the nerve section were several bundles of complex and twisted nerve fibres occasionally showing coiled endings similar to the pictures shown by de Castro (1930), which he describes as that of 'heterogenous regeneration' when there is a considerable gap present. None of these fibres could be traced very far, and it is therefore assumed that they represent unsuccessful attempts at regeneration of the cut rami communicantes. No ganglion cells were present which might have been part of an incompletely resected paravertebral ganglion, and no intermediate ganglia were present.

12TH THORACIC NERVE ROOT

This nerve root was resected with a portion of the subcostal nerve and a ramus communicans. As only one ramus was seen and this accompanied the vessels, it was probably the 'grey' ramus. On comparison with the opposite side it would appear that the more oblique 'white' ramus had been cut during the dissection as it pierced the crus of the diaphragm. No intermediate ganglia were seen at this level.

1ST LUMBAR NERVE ROOT

This nerve root was removed, together with the roots of the genito-femoral and ilio-hypogastric nerves and the branch which joined the 2nd and lower lumbar nerves to form the femoral and obturator nerves. A long 'white' ramus ran obliquely down over the intervertebral disc to disappear in scar tissue at the site of the paravertebral chain at the level of the 2nd lumbar vertebra (Figs. 40 and 45).

Eight intermediate ganglia were discovered in relation to this nerve root. The ganglia have been numbered arbitrarily as they were sectioned—that is, from behind forwards: the more anterior therefore have a higher number. Two small ganglia (Nos. 4 and 5) were present on the 'white' ramus, and another (No. 3) between it and the branch of the anterior primary division going to join the femoral. There was a very large ganglion (No. 6) close to the nerve root, at the site of many fine autonomic fibres, but it appears that it was accidentally damaged during dissection. It is possible to trace a large ramus leaving it towards the lumbar artery, and it is therefore considered that this ganglion was really at the base of the 'grey' ramus—an opinion which is substantiated by the appearance of a similar ganglion and ramus at the same level on the opposite side. Another characteristic small ganglion (No. 8) was present on the anterior primary division close to the origin of the ilio-hypogastric nerve, and others again on the medial side of the nerve root near the origin of the 'grey' ramus (Nos. 1 and 2) and between it and the 'white' ramus (No. 7).

High-power views of No. 8 ganglion show particularly well that, even in the same ganglion, some of the cells have an obviously degenerate appearance (Fig. 35). The cytoplasm of these cells stains much darker with haematoxylin and eosin and having a purple tint—presumably acidophil; the nucleus also stains much darker and there is a loss of nuclear pattern. It was apparent that most of the cells in the ganglia on the 'white' ramus showed such changes and could be compared with obviously normal cells in ganglion No. 6 on the base of the 'grey' ramus. The cells in the 5th lumbar paravertebral ganglion also appeared to be normal (Fig. 36).

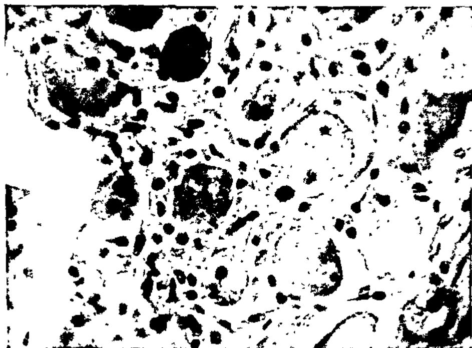


FIG. 37. Cells in No. 6 intermediate ganglion. First lumbar root. H and E × 500.

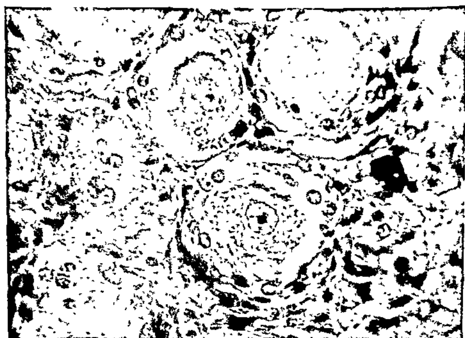


FIG. 38. Cells in first lumbar posterior root ganglion, note 'capsule' Masson's trichrome × 500

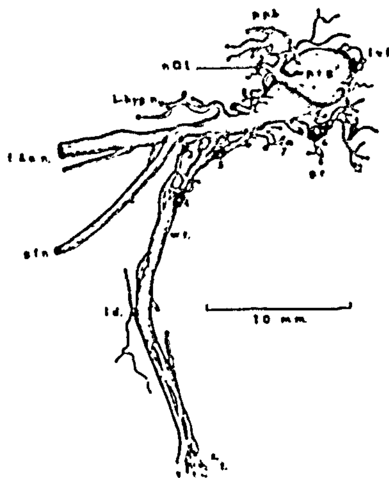


Fig. 40. Projection drawing from transparent model reconstruction. 1st lumbar nerve root (right side); intermediate ganglia Nos. 1–8.

f. & o.n.	to femoral and obturator nerves
g.f.n.	genito-femoral nerve
g.r.	cut 'grey' ramus
i.d.	branches to intervertebral disc, L1/L2
i.hyg.n.	ilio-hypogastric nerve
i.v.f.	site of intervertebral foramen
n.Q.L.	nerve to quadratus lumborum
p.p.b.	posterior primary branches
p.r.g.	posterior root ganglion
s.t.	scar tissue at site of sympathectomy
w.r.	oblique 'white' ramus.

36)—section of a preganglionic fibre does not produce degenerative changes in the cells it supplies.

There can be no question that the cells in these intermediate ganglia are autonomic in type, for there is a considerable difference between them and those in the sensory ganglion of the same root (Fig. 38). Also binucleate cells are fairly common (Fig. 37), whereas they are exceedingly rare in the posterior root ganglia. The autonomic cells in an intermediate ganglion are surrounded by rather less intercellular connective tissue and Schwann cells than they are in a paravertebral ganglion

It was therefore considered that these degenerate cells were those whose axons had passed into the paravertebral chain and had thus been sectioned by the sympathectomy. Obviously those cells on the 'white' ramus were more likely to have suffered in this way, whereas those on

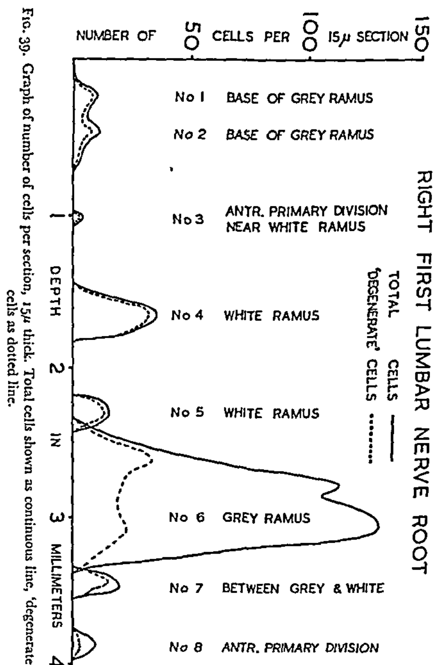


Fig. 39. Graph of number of cells per section, 15μ thick. Total cells shown as continuous line, 'degenerate' cells as dotted line.

the 'grey' ramus should not have been damaged—though their preganglionic fibres might have been sectioned instead. Since all the preganglionic fibres to the 5th paravertebral ganglion were known to have been sectioned (this dermatome was anhidrotic when tested for thermoregulatory sweating) and the ganglion cells here appear normal (Fig.

not all of these cells are degenerate. The sizes of the ganglia and the percentages of abnormal cells they contain, are given in Table IV(a) which summarizes the findings on the ganglia in this nerve root. In all, there were about 6,500 ganglion cells associated with this nerve root.

In order to establish the exact positions and connections of these ganglia, a transparent model was made by projection drawing of the nerve elements present in this nerve root. The fine fibres given off by the 'white' ramus in a medial direction probably supply blood vessels

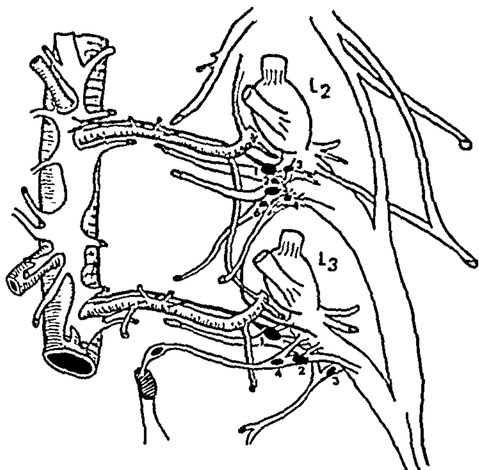


Fig. 42. Diagram of sites and connections of intermediate ganglia in relation to 2nd and 3rd lumbar nerve roots on the left side. Fine nerves accompanying arteries and a nerve loop joining nerve roots are shown as a thick continuous line.

entering the antero-lateral aspect of the body of the vertebra, or possibly supply the intervertebral disc. From this a scale drawing has been prepared, again by projection, and shaded appropriately to give a sense of depth. This drawing (Fig. 40) may therefore be taken as a scale representation of the position of all the intermediate ganglia in relation to this nerve root.

Figure 41 shows a drawing of the second lumbar nerve root on the right side followed by a diagram of the connections of the 2nd and 3rd lumbar nerve roots on the left side (Fig. 42).

which often, in the lumbar region, seems to consist mostly of fibres. The posterior root ganglion cells are larger and appear to have a more granular cytoplasm when stained by Masson's trichrome, and have a well-marked connective tissue capsule.

Multipolar cells could be recognized in intermediate ganglia in sections impregnated with silver on the slide by a modified Bielschowsky method. Even better silver impregnation is seen in sections prepared by Ranson's method (Fig. 48).

Accordingly, the total normal cells and the degenerate cells in this nerve root were counted and their incidence plotted in graphic form

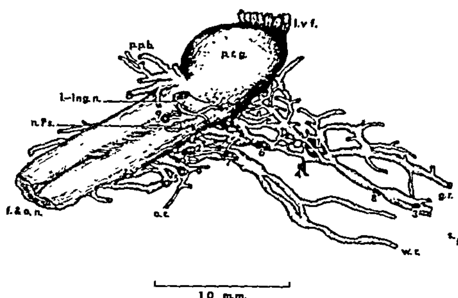


Fig. 41. Projection drawing from transparent model reconstruction. Intermediate ganglia *Nos. 1–9*.

f. & o.n. to femoral and obturator nerves
g.r. 'grey' ramus
i.-ing.n. ilio-inguinal nerve
i.v.f. site of intervertebral foramen
n.Ps. nerve to psoas
o.r. 'oblique' ramus
p.p.b. posterior primary branches
p.r.g. posterior root ganglion
s.t. scar tissue at site of sympathectomy
w.r. 'white' ramus.

(Fig. 39). It will be seen from this that No. 6, No. 7 and No. 8 ganglia contain the greatest relative number of normal cells, and it may therefore be concluded that these ganglia contribute most of the peripheral autonomic fibres that supply the skin in this dermatome. Such behaviour is particularly to be expected from the cells in ganglion No. 8 (Fig. 35), which lies actually on the anterior primary division. The probability that the degenerate cells in the ganglia on the 'white' ramus supply the viscera is discussed again later, but it should be noted that

bundles of the anterior primary division. A low-power view of a section through this root shows the positions and connections of four of these ganglia, including that in the anterior primary division (Fig. 41). One ganglion (No. 4) has at least two rami connecting it with the nerve root, and two others which are directed towards the site of sympathectomy and are distributed on either side of the lumbar artery. Two other smaller ganglia—Nos. 7 and 5—may be seen on the medial side of the anterior primary division (Fig. 43) and appear to have many rami connecting them to it and each other, and to another ramus which lies rather more superficial and inferior in position to the two rami around the lumbar artery. It was therefore considered that this most distal ramus was of the 'white' variety, though it was less oblique in position than that of the 1st lumbar nerve. There was a small ramus running out from the No. 5 ganglion which passed deep down towards the 3rd lumbar root. This was possibly an anastomotic loop connecting it with this root, and which was seen in a similar position, but more clearly, on the left side. No. 9 ganglion, which was situated in the anterior primary division, was quite small, but was seen to contain a binucleate cell and

Table IV(b)

Ganglion number	*Position*	*Estimated maximum number of cells in section*	*Approximate size of ganglion (microns)*	*Appearance of cells*
	2nd Lumbar Nerve Root: Right			
1	On posterior 'grey' ramus	6	200 × 150 × 300	Mostly normal Few degenerate
2	Anterior to 'white' ramus at base	30	600 × 300 × 400	Mostly normal Few degenerate
3	Far out along 'grey' ramus	1	— —	Normal
4	On base of 'grey' ramus (a)	35	800 × 400 × 500	Mostly normal Few degenerate
	(b)	20	200 × 200 × 100	
5	On anterior side of 'white' ramus (a)	24	300 × 400 × 200	Mostly normal Some degenerate
	(b)	1	— —	
	(c)	6	150 × 100 × 200	
6	On 'grey' ramus near base	4	100 × 200 × 100	Normal
7	On base of 'white' ramus (a)	75	1000 × 300 × 700	Mostly normal Some degenerate
	(b)	1	— —	
	(c)	1	— —	
8	Far out along 'grey' ramus (a)	3	200 × 100 × 100	Normal
	(b)	3	200 × 100 × 100	
9	In middle of anterior primary division	3	200 × 100 × 100	Normal

Table IV(a)

Ganglion number	*Position*	*Estimated maximum number of cells in section*	*Approximate size of ganglion (microns)*	*Number of cells*	*Approximate percentage of 'degenerate' cells*
	1st Lumbar Nerve Root: Right				
1	Medial to intervertebral foramen at base of 'grey' ramus	6	200 × 100 × 200	250 (ganglia 1 and 2)	64 (ganglia 1 and 2)
2	More medial to intervertebral foramen at base of 'grey' ramus	12	400 × 150 × 200		
3	On course of anterior primary division near 'white' ramus	2	100 × 100 × 100	18	44
4	On 'white' ramus communicans	40	200 × 300 × 500	615	83
5	Column of cells along 'white' ramus	16	200 × 500 × 50	175	82
6	Close to body of vertebra near intervertebral foramen at base of 'grey' ramus	150	1000 × 1500 × 1000	5,210	25
7	Near intervertebral foramen between 'grey' and 'white' rami	20	200 × 400 × 200	205	69
8	On course of anterior primary division near origin of ilio-hypogastric nerve	12	200 × 300 × 200	103	24
			Total	6,576	29

Total number of cells on this nerve root is more than this number since ganglion No. 6 was damaged during dissection and many cells are missing.

2ND LUMBAR NERVE ROOT

Though the intermediate ganglia associated with this nerve root were not so large as No. 6 ganglion on the 1st lumbar root, they were rather more numerous and scattered than those seen before. There were in all, nine major ganglion groups (sometimes sub-divided *a*, *b*, *c*), and these included a small ganglion consisting of a few cells actually in the nerve

4TH LUMBAR NERVE ROOT

This nerve root received a large contribution from those above it towards the femoral and obturator nerves. It also gave off two smaller branches to join the lumbosacral trunk, and others, like those above it, to the psoas and quadratus lumborum muscles. A single large 'grey' ramus joined the upper end of the remaining lower portion of the paravertebral chain at the level of the body of the 4th lumbar vertebra. Another ramus just below this ran back obliquely downwards from the paravertebral ganglion at this level, towards the 5th lumbar nerve root.

Near the base of the 'grey' ramus there was a large intermediate ganglion which had a number of its own rami leaving and joining the nerve root at different levels. The staining reactions of the cells suggested that they were quite normal—though, of course, their preganglionic fibres had been cut. There were many more fibres passing through this intermediate ganglion than is usual—indeed, the general appearance was much more like a paravertebral ganglion.

5TH LUMBAR NERVE ROOT

This nerve root contributed mostly to the lumbosacral trunk and received two branches from the 4th lumbar nerve above it. It was connected with an elongated paravertebral ganglion lying over the body of the 5th lumbar vertebra by two rami, the lower of which was very fine and ran superficially to accompany the blood vessels. The upper pierced the ilio-lumbar ligaments and connected with the oblique descending ramus from the 4th lumbar paravertebral ganglion.

Only a few scattered autonomic ganglion cells were found in this ramus near the nerve root, but subsequent section of the 5th lumbar paravertebral ganglion showed a process of cells from the paravertebral ganglion extending out along the ramus.

The findings on the intermediate ganglia on the lower thoracic and lower lumbar nerve roots are summarized in Table IV(*c*).

A diagrammatic reconstruction of all the relevant nerve roots, and their rami, on the right side shows the position of the lumbar intermediate ganglia, of which there were twenty on this side. The photograph originally taken of these nerve roots before they were embedded is placed alongside for comparison. The intermediate ganglia have been shown approximately to scale and have been outlined to facilitate their recognition (Fig. 45). The probable position of the 'grey' ramus connected to the 1st lumbar nerve root, which was cut during dissection, is shown with a dotted line. The probable position of the resected sympathetic chain is shown with a dashed line.

therefore cannot possibly be a displaced sensory ganglion. The cells elsewhere in the ganglia on this root mostly appeared quite normal, but occasional degenerate cells could be seen in the ganglia associated with the more superficial or 'white' ramus as in No. 7 ganglion. No accurate count of the cells was made on this root, but they were estimated at about the same number as those associated with the 1st lumbar root, though a far smaller proportion were degenerate. The findings have been summarized in Table IV(*b*), and a reconstruction drawing prepared in a similar manner to that of the 1st lumbar root. This shows the position and complicated arrangement of the rami communicantes to the site of the paravertebral chain and the rami between the individual ganglia (Fig. 41). To the left is the anterior primary division contributing to the origin of the femoral and obturator nerves, and from which arise the ilio-inguinal nerve and a branch to the psoas. Branches of the posterior primary division are seen above this and nearer to the posterior root ganglion. The three main bundles of the rami communicantes are seen on the right.

3RD LUMBAR NERVE ROOT

Sections showed two rami leaving this root, but only the lower one was found to be the true 'grey' ramus. The upper structure was the lumbar artery which was accompanied by some fine autonomic fibres. The lateral cutaneous nerve of the thigh arose from this nerve root and from the contribution of the 2nd lumbar to the femoral and obturator nerves.

A very large intermediate ganglion was found at the base of the 'grey' ramus, close to a longitudinal anastomozing (pre-costal) artery joining the lumbar arteries. The ganglion contained a great number of cells, and all of these appeared normal. This is to be expected, since the 3rd lumbar nerve root is below the usual level of the thoraco-lumbar outflow and therefore these cells should not send their postganglionic fibres towards the viscera. Indeed, it is probable that all the preganglionic fibres which must have passed to the cells of this ganglion through the paravertebral chain must have been cut by the sympathectomy. No thermoregulatory sweating was present in the lower part of this dermatome, so the preganglionic fibres to these cells cannot have remained intact.

At the time of the original dissection it was noted that the ramus from this root just failed to join the upper end of the remaining caudal portion of the paravertebral chain at the level of section at the lower border of the 3rd lumbar vertebra. Some fibres from this ramus could be traced beneath the inferior vena cava, still accompanying the lumbar artery towards the ganglion tissue on the side of the aorta.

Table IV(c)

Ganglion number	*Position*	*Estimated maximum number of cells in section*	*Approximate size of ganglion (microns)*	*Appearance of cells*
	3RD LUMBAR NERVE ROOT: Right			
—	At base of ramus medial to anterior primary division	80	1500 × 500 × 1000	All normal
	4TH LUMBAR NERVE ROOT: Right			
—	At base of ramus medial to anterior primary division; has separate 'grey' and 'white' rami	70	200 × 700 × 750	All normal
	5TH LUMBAR NERVE ROOT: Right			
1	Along ramus	Few scattered cells only		
2	Also process of cells extending out from paravertebral ganglion	50	1000 × 300 × 300	All normal
	9TH THORACIC NERVE ROOT: Right			
	No intermediate ganglia found			
	12TH THORACIC NERVE ROOT: Right			
	No intermediate ganglia found			

§1B. THE LUMBAR INTERMEDIATE GANGLIA—LEFT SIDE

The nerve roots on the left side had been left untouched while those on the right side were being sectioned: the block of the vertebral column and nerve roots which had been removed from the body originally had remained in the formalin fixative. In order to determine the sites and connections of the ganglia on this side, the nerve roots were impregnated with silver by a modification of Ranson's method—variations of which were first tried out on less important nerve roots and ganglia. As the rami between the nerve roots and the intermediate ganglia were so fine, a large block of tissues was dissected away from the vertebral skeleton, and this included all the relevant nerve roots, their rami communicantes, the scar tissue at the site of the resected sympathetic chain, and the remaining paravertebral ganglia, and the ganglionic tissue on the side of the aorta and its branches. As the resection of the para-

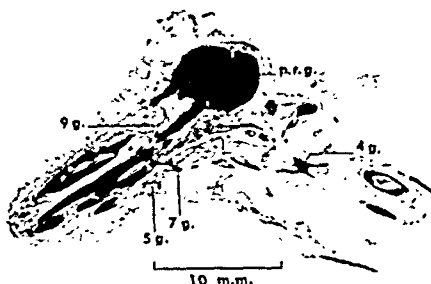


FIG. 43. Second lumbar nerve root (right side). H and E × 2·7.

9g.	site of No. 9 ganglion
5g. & 7g.	Nos. 5 and 7 ganglia
p.r.g.	posterior root ganglion
4g.	No. 4 ganglion



FIG. 44. Second lumbar nerve root (right side). No. 7 ganglion on 'white' ramus. H and E × 82.

foramina. The whole sheet of tissue was then dissected forward in one piece. The knife was kept close to the periosteum and to the edge of the fibrous tissue of the annulus fibrosus of the disc, which here left gaps between the soft tissue containing the lumbar vessels and rami. The transverse processes and ribs were divided as required to facilitate exposure of the nerve roots.

This large block of tissue was again photographed and from it were cut thirteen smaller blocks of tissue which were of a suitable size for sectioning.

These blocks were all impregnated with silver by a modified Ranson's method and embedded in wax with small rectangular blocks of liver so that the serial sections would always be in correct register. The blocks were photographed again while in the molten wax so that any particular nerve could always be reorientated into its correct position. The sections were cut from behind forwards at 15 μ as before, but only every tenth was mounted initially: in the more important regions some or all of the intermediate sections were mounted later.

In preparing a diagrammatic reconstruction, sections at regular intervals from certain of the more important blocks, such as those of the 2nd and 3rd lumbar nerve roots, were projected on to photographic paper and measurements of the intermediate ganglia and their rami accurately recorded.

In other blocks the slides were marked with ink and these indications superimposed on the photographs of the blocks taken after embedding, and then onto the others taken before impregnation with silver. In this way it is hoped that all the connections shown are complete in the relevant area.

A more accurate method would have been to impregnate, embed and section the whole piece of tissue in one block, but since it measured approximately 9 × 5 inches this would have been technically very difficult! Such a method might be used, however, on small animals or larger human foetuses. It has the advantage that most of the rami are cut in the plane of their fibres, since the curve around the sides of the lumbar vertebrae is flattened in embedding.

The findings on the right side had suggested that although the intermediate ganglia situated far out along the 'white' ramus from the 1st lumbar nerve contained mostly degenerate cells, yet there were still about 15 per cent. which appeared normal. Possibly these cells sent postganglionic fibres which, if they passed in a medial direction, must have escaped section by the paravertebral resection. Special attention therefore was paid to the possibility that fibres might leave the 'white' rami before entering the paravertebral chain. Similarly, if the intermediate ganglia at the base of a 'grey' ramus contained some degenerate cells (25 per cent. in No. 6 ganglion of 1st right lumbar nerve root),

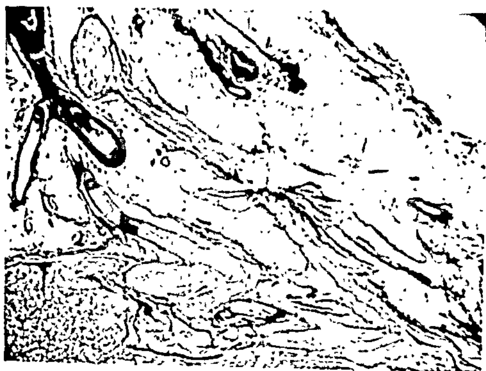


FIG. 46. No. 4 ganglion in second lumbar nerve root (left side). Silver × 12.



FIG 47. Grey ramus accompanying artery. Silver × 30.

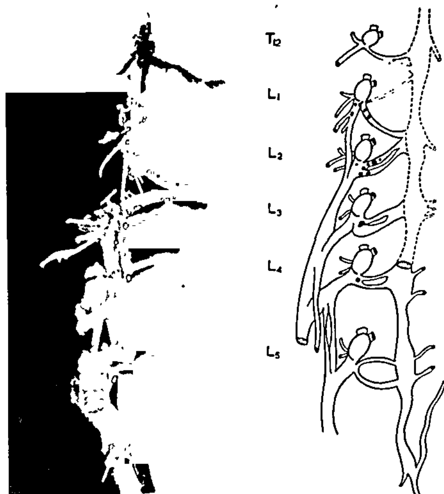


FIG. 45 Nerve roots T.12 to L.4 (right side) with rami communicantes. To show position of lumbar intermediate ganglia.

then presumably the 'grey' ramus must have contained postganglionic fibres which passed towards the paravertebral ganglion—though it is possible that they did not all go to the viscera, but passed back again in a ramus to the same or another nerve root. If, however, some of the normal cells had sent fibres in the same direction, then these fibres must have remained intact—such a pathway might be along a course accompanying the lumbar artery which is not involved in the paravertebral resection. Indeed, a fine nerve in this position had been seen in 9th thoracic nerve root on the right side, though no intermediate ganglion was present at this level.

As the 1st lumbar ganglion on the left side had been left behind and was still connected to the 1st lumbar nerve root, intermediate ganglia in the 'grey' root of the latter would not be expected to contain degenerate cells. Also it would have been much more difficult to determine definitely whether any fine rami accompanying the 1st lumbar artery had received reinforcement from the paravertebral ganglion or had remained as a single bundle. For these reasons greater attention was paid to the connections of the 2nd and 3rd lumbar nerve roots on this side, since it seemed probable that they would yield the most information.

FINDINGS

11TH THORACIC NERVE ROOT

This nerve root sent its 'white' ramus obliquely downwards through the crus of the diaphragm and, anterior to the paravertebral sympathetic chain, towards the superior mesenteric ganglion around the aorta. A small intermediate ganglion was found deep in relation to the vertebral branch of the subcostal artery and should therefore be considered as placed far out on the 'grey' ramus of the 12th thoracic nerve.

12TH THORACIC NERVE ROOT

This nerve root sent a large oblique 'white' ramus to join the 1st lumbar paravertebral ganglion which had been left behind. This ramus ran behind the crus of the diaphragm and in its upper part was covered by pleura. No intermediate ganglia were found other than the one described above, which was on the more horizontal 'grey' ramus.

1ST LUMBAR NERVE ROOT

A large 'grey' ramus accompanied the 1st lumbar artery to join the 1st lumbar ganglion which had been left behind. The ramus lay inferior to the artery at a deep level, but gave off a small branch which ran between the artery and vein on the upper side of the artery and appeared to pass behind the 1st lumbar paravertebral ganglion, but could not be followed farther with certainty. There was a large intermediate ganglion



Fig. 48. Multipolar intermediate sympathetic ganglion cells. Ranson's silver (modified) × 640.

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Fig. 48. Multipolar intermediate sympathetic ganglion cells. Ranson's silver (modified) × 640.

be followed right across beneath the scar in company with the lumbar artery to the medial edge of the block. Here, though the branches were much reduced in size, the fibres in them still appeared to be intact. Indeed, high magnification enabled the individually silver-impregnated fibres to be seen beneath the site of the resection of the sympathetic chain, and could be compared with a nearby nerve bundle which had lost its Schwann nuclei and was interwoven with collagen fibres—presumably the latter nerve bundle had degenerated, but in the bundle accompanying the artery the fibres were quite normal.

At a more superficial level, small bundles from the 'white' ramus could be followed into the scar tissue, and in certain situations fine individual fibres could be followed for distances even up to 2 mm. The impregnation of these fibres was better than usual, possibly due to the fact that they were so close to the surface in the sympathectomy scar tissue. They were probably regenerating fibres and, if so, would have had about another centimetre to grow before they would reach the ganglion cells on the sides of the aorta.

The small bundle of fibres, which had continued across the block of the site of the 2nd lumbar ganglion in company with the lumbar artery, was followed into the block of the aortico-renal ganglion and surrounding tissue. These small nerves still appeared to be quite normal and were found in relation to blood vessels.

Another moderate-size intermediate ganglion (No. 2) was present between the 'grey' and 'white' rami and two more in relation to the 'white' ramus. One of these (No. 6) sent a fine ramus obliquely downwards as though to join the paravertebral chain in a similar position to that of the 'white' ramus from the 1st lumbar nerve root. It could not be followed beyond the site of resection of the 3rd lumbar paravertebral ganglion. Another fine ramus was given off from No. 4 ganglion and accompanied a longitudinal 'precostal' branch from the 2nd lumbar artery to join the 3rd lumbar artery. It appears that this fine nerve loop must be the same as that described by Alexander *et al.* (1949) and Ehrlich and Alexander (1951). At intervals it was seen to give off fine twigs to the artery, until it eventually joined the 3rd lumbar nerve root. A larger branch from this nerve coursed towards the 3rd lumbar artery nearer the aorta, but could not be followed farther as it disappeared in scar tissue.

This nerve root gave off another branch to the genito-femoral nerve, and its main portion passed into the femoral, obturator and accessory obturator nerves.

3RD LUMBAR NERVE ROOT

This nerve root possessed a very large intermediate ganglion (No. 1) at the base of the larger and deeper 'grey' ramus which lay close to the artery. Another ramus placed more superficially and which joined the

(No. 2) at the base of the larger grey ramus which was connected with the anterior primary division by a more superficial ramus of its own. This ganglion sent a branch to the fine ramus described above which accompanied the artery and vein. A small intermediate ganglion (No. 1) lay on the anterior primary division just proximal to this ramus.

A large (No. 3) and two smaller (Nos. 4 and 5) intermediate ganglia were found at the base of the oblique and more superficial 'white' ramus—No. 5 ganglion was placed close to the origin of the genito-femoral nerve. The white ramus could be followed into the block at the site of the 2nd lumbar paravertebral ganglion, but here the fibres were seen to fan out into the fibrous tissue—indeed, under a higher power only fine fibres could be seen interspersed with collagen and relatively few Schwann cell nuclei. It appears, therefore, that most of the fibres in this ramus had degenerated. Indeed, some of the cells in the intermediate ganglia at its base—especially ganglion No. 3—showed changes in the cells similar to those seen on the opposite side, but, being impregnated with silver, the appearance was not so definite as that revealed by haematoxylin and eosin or Heidenhain's iron-haematoxylin, and therefore no attempt was made to estimate the numbers of degenerate cells.

This nerve root gave off branches to the lateral cutaneous nerve of the thigh and to the genito-femoral nerve. It also sent a contribution to join the 2nd lumbar nerve, to the femoral, obturator and accessory obturator nerves.

2ND LUMBAR NERVE ROOT

This root sent two rami horizontally towards the site of the 2nd lumbar paravertebral ganglion. The lower and more superficial ramus was taken to be the 'white' ramus and was in a similar position to that on the opposite side. A large intermediate ganglion (No. 5) on the 'white' and more superficial ramus can be seen in relation to the lower side of the artery, and its rami join the nerve root more distally (Fig. 46). Another but deeper ramus, which leaves the nerve root closer to the posterior root ganglion, runs up under a branch of the lumbar artery. At a deeper level this 'grey' ramus continued into another large intermediate ganglion (No. 1), from which it continued its course close to the lumbar vessels. The multipolar character of the cells in this ganglion is well seen in Fig. 48. A smaller ganglion (No. 3) was situated at the base of the 'grey' ramus close to the anterior primary division. Another smaller branch of the 'grey' ramus was followed up into the block of the site of the 2nd lumbar paravertebral ganglion where it could be seen between the artery and the vein (Fig. 47). Although most of the fibres ended in scar tissue at about the level where another artery branches off—presumably to supply the sympathetic chain—some of them could

more superficial ramus to join the anterior primary division more distally. A branch from this ramus accompanied an anastomozing artery, between the 4th lumbar artery and the ilio-lumbar artery, to join the 5th lumbar nerve root close to the intervertebral foramen. The less usual position of this nerve junction is probably to be explained by the absence of the 5th lumbar artery and the different arrangement of the blood vessels around this nerve root.

5TH LUMBAR NERVE ROOT

This root was also connected to the paravertebral sympathetic chain by a superficial and a deeper 'grey' ramus. The latter branched again before it joined the chain and in the upper of these branches there was a process of ganglion cells similar to that found on the opposite side. The outflow from this nerve root received a contribution from the 4th lumbar nerve root and continued across the ala of the sacrum as the lumbo-sacral trunk.

The findings of the intermediate ganglia on the left side have been summarized in Table V. In all, eighteen such ganglia were present in the lumbar region on this side as compared with twenty on the right side. Though no special cell count was attempted, it is thought that there were about the same number of cells on each side.

A diagrammatic reconstruction, similar to that of the right side, has also been prepared of the left nerve roots, rami and ganglia (Fig. 49). It is shown beside the photograph of the original piece of tissue obtained from the dissection, and the intermediate ganglia are outlined in both to facilitate identification. The fine rami which accompany the lumbar arteries and the loops between certain nerve roots are shown as a thick continuous line. It seems most probable that these fine rami contain postganglionic and sensory fibres to the arteries they accompany. It is possible, however, that preganglionic fibres may accompany them, since Pick and Sheehan (1946) have shown that the horizontal and oblique rami connecting as low as with the 2nd lumbar nerve root may contain myelinated and unmyelinated portions included together in the same bundle. Indeed, Pick and Sheehan examined in detail the rami communicantes in the lumbar region on seven sides. The oblique so-called 'white' rami were sometimes duplicated, but were twice of the mixed variety and once purely unmyelinated in relation to the 1st lumbar nerve. They were thrice mixed and twice unmyelinated in relation to the 2nd lumbar nerve. It is probable that the unmyelinated portions of these nerves originated from cells in intermediate ganglia at the base of the 'white' ramus. Though they reported that all the transverse rami connected to the 1st lumbar nerve root were unmyelinated, they found that they were of the mixed variety in two

anterior primary division more distally also coursed towards the site of the 3rd paravertebral ganglion. This ramus was in a similar position to the larger ramus on the opposite side and to the 'white' ramus of the 2nd lumbar nerve root. It is possible, therefore, that this ramus contained myelinated preganglionic fibres, but as it is rare for the 3rd lumbar nerve to do so (this case had a pre-fixed lumbar plexus), it will be considered as a superficial 'grey' ramus. Attempts to stain the rami from the 2nd and 3rd lumbar nerves on the right side for myelin by Weigert's method and its modifications have not been successful, and it cannot be said definitely whether or not these more superficial rami from the 2nd and 3rd lumbar nerve roots contain myelinated preganglionic fibres, although there must be some to supply the intermediate ganglia on these rami. The appearance of the silver-impregnated sections suggested that the fibres are not all of the same type or diameter.

A small ramus from the intermediate ganglion (No. 1) on the deeper ramus was found to accompany the lumbar artery across the site of sympathetic resection until it joined the ganglion tissue on the side of the aorta at the level of the inferior mesenteric artery. Two small intermediate ganglia (Nos. 2 and 4) were present at the base of the superficial 'grey' ramus, and a few cells were found at its distal end beneath the scar tissue of the sympathectomy. Presumably these cells had extended out along the ramus from the paravertebral chain and had thus escaped complete resection: their appearance suggested that they had all degenerated.

Another small intermediate ganglion (No. 3) was found close to the nerve root beneath the superficial 'grey' ramus. This ganglion sent an oblique descending ramus towards the 4th lumbar paravertebral ganglion. Although this ramus accompanied a small longitudinal 'precostal' artery, it did not appear to form a nerve loop with the 4th lumbar nerve root.

The particular connections of the ganglia and rami in relation to the 3rd and 4th lumbar nerve roots and to the lumbar arteries and their branches are shown in the diagram (Fig. 42). The fine nerves accompanying the lumbar arteries and the loop between the nerve roots are shown as a thick continuous black line. The aorta is on the left and gives off the left aberrant renal and inferior mesenteric arteries. The autonomic ganglion tissue on the sides of the aorta is shown in white, but the intermediate ganglia emphasized in black and numbered.

4TH LUMBAR NERVE ROOT

This nerve root also had a superficial and a deep 'grey' ramus connecting with the paravertebral sympathetic chain on the body of the 4th lumbar vertebra. There was a small elongated intermediate ganglion about half-way along the deeper ramus which sent back a

Table V(b)

Ganglion number	*Position*	*Maximum number of cells in section*	*Approximate size of ganglion (microns)*
	2ND LUMBAR NERVE ROOT (LEFT)		
5	Base of 'grey' ramus—deeper part	200	1500 × 1000 × 1000
6	Beneath 'grey' ramus, sends connections to oblique descending ramus	20	600 × 200 × 200
	3RD LUMBAR NERVE ROOT (LEFT)		
1	Base of 'grey' ramus, deep part. Connects with ramus along lumbar artery	120	2000 × 600 × 1500
2	Base of 'grey' ramus superficial part near anterior primary division	20	150 × 700 × 200
3	Beneath 'grey' ramus, sends connections to oblique descending ramus	16	200 × 200 × 300
4	Farther out along superficial 'grey' ramus	20	300 × 300 × 500
—	Small process of cells extending from paravertebral chain into inferior 'grey' ramus	6	200 × 200 × 200
	4TH LUMBAR NERVE ROOT (LEFT)		
—	Far out along 'grey' ramus connecting with loop to L.5 nerve root	20	400 × 500 × 1200
	5TH LUMBAR NERVE ROOT (LEFT)		
—	Far out along deeper 'grey' ramus close to paravertebral chain	135	3500 × 500 × 600

ports of dissections in the human foetus by Mitchell (1935) and his conclusions in regard to the extent of sympathectomy required to denervate the viscera (Mitchell, 1947). Since, however, there was evidence of early attempts at regeneration across the site of the resected paravertebral chain at the level of the 2nd lumbar vertebra, it would seem that special attention should be paid to the resection of the lower end of the chain rather than to attempt to extend the resection upward. In this respect it is of interest to consider the experimental work on puppies by Papez, Jansen and Dukes (1945). These workers found that two years after paravertebral sympathectomy 'pseudo-sympathetic' trunks and splanchnics were seen, which produced no response on electrical stimulation. Subsequent section showed that these false nerve trunks

Table V(a)

Ganglion number	*Position*	*Maximum number of cells in section*	*Approximate size of ganglion (microns)*
	11TH THORACIC NERVE ROOT (LEFT)		
	No intermediate ganglia found		
	12TH THORACIC NERVE ROOT (LEFT)		
	Small ganglion far out along 'grey' ramus close to paravertebral chain	20	300 × 300 × 200
	1ST LUMBAR NERVE ROOT (LEFT)		
1	Between 'grey' and 'white' rami medial to intervertebral foramen	12	400 × 200 × 200
2	Base of 'grey' ramus—sends ramus along lumbar artery	60	600 × 500 × 300
3	Base of 'white' ramus—deeper	70	600 × 400 × 1200
4	Base of 'white' ramus close to anterior primary division	10	200 × 150 × 150
5	Base of superficial part of 'white' ramus and close to root of genitofemoral nerve	300	600 × 400 × 400
	2ND LUMBAR NERVE ROOT (LEFT)		
1	Base of 'grey' ramus—deeper part. Sends ramus along lumbar artery	150	2000 × 1000 × 1200
2	Deep between 'grey' and 'white' rami	75	1000 × 400 × 300
3	On anterior primary division near 'grey' ramus	6	100 × 600 × 200
4	Base of 'white' ramus—more superficial part nearer anterior primary division, sends connections to loop with L.3 nerve root	6	100 × 100 × 100

cases. It seems, therefore, that the constitution of 'grey' and 'white' rami should be reconsidered in relation to the knowledge that intermediate ganglia can exist in relation to both of them. It is for this reason that the terms 'grey' and 'white'—where used here—are put in parenthesis. Autonomic impulses in preganglionic or postganglionic neurones can probably proceed in a distal (i.e. medial) direction in both of them.

The reconstruction shows that normally the upper three lumbar nerves can supply preganglionic fibres to the viscera via the paravertebral sympathetic chain. This work therefore confirms earlier re-

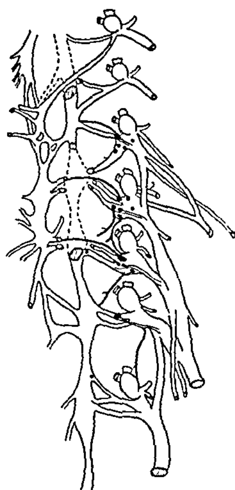




FIG. 49. Nerve roots T.11 to L.5 (left side) with rami communicantes and sympathetic ganglia on sides of aorta, from which arise an aberrant renal artery and the inferior mesenteric artery. To show position and connections of lumbar intermediate ganglia. Fine nerves accompanying lumbar arteries and loops between nerve roots are shown as a thick continuous line.

were mainly composed of perineural strands surrounded by connective tissue. Also there appeared to be postganglionic vasomotor nerves of a moderate amount coming from coeliac and periadrenal ganglia which were not affected by the sympathectomies. It seems probable, therefore, that these intact pathways were from the intermediate lumbar ganglia of which Papez and his co-workers were not aware.

Although no accurate count was made of the number of cells in that part of the 1st lumbar and part of the 12th thoracic paravertebral ganglion which had been left behind at operation, it was calculated that approximately 7,000 cells were present in that part of chain in relation to the 'grey' ramus to the 1st lumbar nerve root. This may be compared with an almost equal number of cells counted in the intermediate ganglia in relation to the same nerve root on the opposite side. Webber (1958) has counted almost 60,000 cells in a complete paravertebral ganglion at the level of the 1st lumbar vertebra. Unfortunately he makes no mention of the number of cells in the intermediate ganglia at this level, though he counted 10,000 cells in such a ganglion related to the 3rd lumbar nerve. It is evident, therefore, that the cells of the intermediate ganglia exert a very considerable measure of autonomic activity at these levels.

§2. CORRELATION BETWEEN SWEATING PATTERN OF THE 'ESCAPE' AREA AND ANATOMICAL FINDINGS

OBSERVATIONS IN THE HUMAN EMBRYO AND FOETUS

It will be remembered that in the diagram of the sweating pattern of this Case s.s. (Fig. 34), the upper border of the 'escape' area was asymmetrical, and reached into the L.1 dermatome on the right, but on the left it extended higher into the T.12 dermatome. The postmortem findings indicate that sweating on the right side in the L.1 dermatome must have been produced by nerve fibres from the intermediate ganglia associated with the 1st lumbar nerve root—for that is the highest level at which they were found on this side. On the left side, the T.12 dermatome was probably supplied from the small intermediate ganglion on the horizontal 'grey' ramus from the 12th thoracic nerve or from the small portion of the paravertebral chain which had been left behind at the level of the 12th thoracic and 1st lumbar vertebrae. The correlation between the sweating pattern and the occurrence of intermediate ganglia can therefore be established in this case, and it appears that the overlap of nerve supply extends upwards one segment. Similarly, the lower level of the sympathetic outflow in this case was probably in the 2nd lumbar nerve root and the rami were symmetrical on either side. The intermediate ganglia in association with this nerve

root therefore sent sudomotor fibres as far as the lower level of the L.2 dermatome—for it will be remembered that although symmetrical sweating did not appear to extend as far down the inside of the legs as was usual in most other cases. This can be explained by the occurrence of a pre-fixed lumbar plexus in this case and presumably in the other eight sides which show this type of pattern.

The intermediate ganglia in association with the 3rd and 4th lumbar nerve roots on each side in this case must have been supplied by preganglionic fibres which had passed down the paravertebral chain and had been resected at the level of the 3rd lumbar vertebra or above. These intermediate ganglia are therefore in a similar position to those paravertebral sympathetic ganglia at the level of the 4th lumbar vertebra and those below it (Fig. 32). Indeed, the normal appearance of the cells in these two sets of ganglia suggests that this is so and that their postganglionic fibres are intact.

OCCURRENCE IN THE EMBRYO AND FOETUS

An excellent review of our knowledge of the earlier development of the autonomic nervous system was made by Yntema and Hammond (1947), but the intermediate ganglia were not described although Wrete had made the first report on their presence in the human foetus in 1934 (*a* and *b*).

Boyd has reported (1950 and 1957) that in a 100-mm. *c.r.* human foetus in his collection nineteen intermediate ganglia were present in the lumbar region on one side (Fig. 31). They were present in much the same positions as in the adult material described earlier, and were particularly frequent around the base of the anterior primary division fairly close to the posterior root ganglion, from which, however, they may be easily distinguished, particularly in silver-impregnated material, by the later development of the cells in the intermediate ganglia and by their tendency to form 'rosettes' with the nuclei around the edge (in this respect they are similar to the 'pseudo-rosettes' seen in neuroblastoma tumours).

Two small intermediate ganglia may be seen on either side of the base of the anterior primary division on the left side in a low-power view of a 60-mm. *c.r.* human foetus (Fig. 50). In this section the spinal cord may be seen below, and above this is the body of the lumbar vertebra, and in the mid-line in front of this is the aorta. On either side of the body of the vertebra are the psoas muscles and the kidneys. At the anterior edge of the psoas muscles on either side are the paravertebral sympathetic ganglia and their rami. The rami communicantes between the nerve roots and the sympathetic chain are not seen in this others they may be seen to pass through the psoas muscle

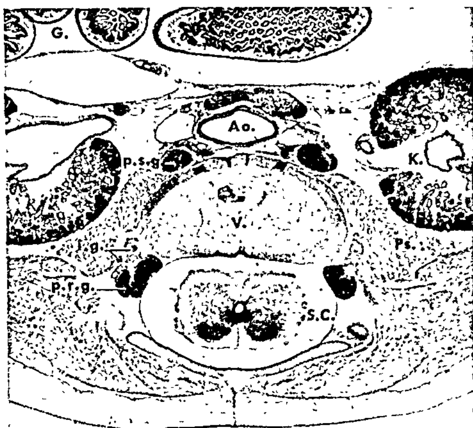


FIG. 50 Transverse section of a 60-mm. c.r. human foetus showing sites of two lumbar intermediate ganglia. H and E × 16.

G. coils of small gut
Ao. aorta
p.s.g. paravertebral sympathetic ganglion
i.g. intermediate ganglia
p.r.g. posterior root ganglion
K. kidney
V. lumbar vertebral body
Ps. psoas muscle
S.C. spinal cord in spinal canal

pear much less frequently in Wrete's subjects, since they are shown as having six, fourteen, two and ten respectively. Those marked 'm' were macroscopically visible. Wrete himself wondered if the large variation in number had any significance—two to fourteen ganglia; but he com-

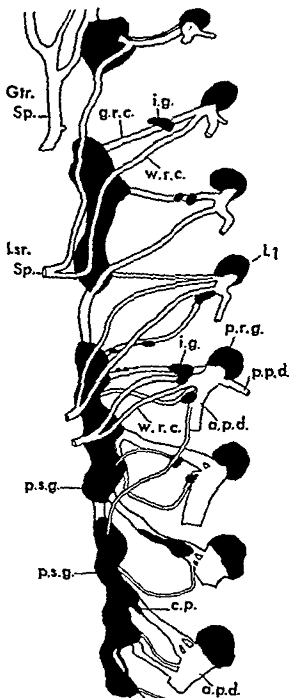


FIG. 52. Reconstruction of sympathetic intermediate ganglia and rami communicantes in human foetus (redrawn). Wrete, M. (1943). *Z. mikr.-anat. Forsch.*

a.p.d.	anterior primary division
c.p.	cellular process from sympathetic chain
g.r.c.	grey ramus communicans
Gtr. Sp.	greater splanchnic nerve
i.g.	intermediate ganglia
L_1	1st lumbar nerve root
Lsr. Sp.	lesser splanchnic nerve
p.p.d.	posterior primary division
p r.g.	posterior root ganglion
p.s.g.	paravertebral sympathetic ganglia
w.r.c.	white ramus communicans.

pares it with the variation shown in the number of intermediate ganglia in his embryos, which he found to be between three and seventeen, and suggests the difference in numbers may be purely accidental due to the great individual variation.

In the same paper, however, Wrete shows a profile reconstruction of

around the sides of the body of the vertebrae to reach the sympathetic chain. The 'grey' ramus often accompanies the lumbar artery.

Of particular interest is the occurrence of intermediate ganglia in relation to the posterior primary division. These are found more rarely, but two were seen in a silver-impregnated foetus of 68-mm. *c.r.*

Although detailed counts of the lumbar intermediate ganglia have not yet been made on all the embryos and foetuses in Professor Boyd's collection, they have constantly been found in relation to the upper two

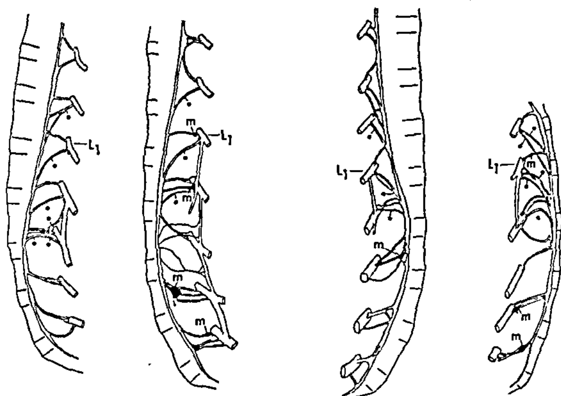


Fig. 51. Four adult subjects showing position of sympathetic intermediate ganglia and connections to rami communicantes (redrawn). Wrete, M. (1943). *Z. mikr.-anat. Forsch.*

L_1 first lumbar nerve root in each case
m intermediate ganglia which are macroscopically visible
o superficial ramus communicans.

lumbar nerves, frequently in relation to the other lumbar nerves, and occasionally on the lower thoracic and 1st sacral nerves. On one side in a 100-mm. foetus, nineteen lumbar intermediate ganglia were present (Fig. 31), which compares well with eighteen and twenty ganglia found on either side of the adult subject described here.

The only other detailed published descriptions of lumbar intermediate sympathetic ganglia in the adult are on single sides—two left and two right in four subjects dissected by Wrete (1943). The positions of the ganglia are shown (Fig. 51) in the figures taken from this paper, and should be compared with those on each side of the subject described here (Figs. 45 and 49). It will be noticed that intermediate ganglia ap-

pear much less frequently in Wrete's subjects, since they are shown as having six, fourteen, two and ten respectively. Those marked 'm' were macroscopically visible. Wrete himself wondered if the large variation in number had any significance—two to fourteen ganglia; but he com-

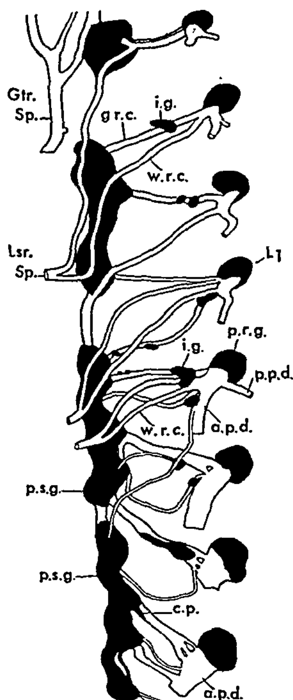


Fig. 52. Reconstruction of sympathetic intermediate ganglia and rami communicantes in human foetus (redrawn). Wrete, M. (1943). *Z. mikr.-anat. Forsch.*

a.p.d.	anterior primary division
c.p.	cellular process from sympathetic chain
g r.c.	grey ramus communicans
Gtr. Sp.	greater splanchnic nerve
i g.	intermediate ganglia
L_1	1st lumbar nerve root
Lsr. Sp.	lesser splanchnic nerve
p.p.d.	posterior primary division
p.r.g.	posterior root ganglion
p.s.g.	paravertebral sympathetic ganglia
w.r.c.	white ramus communicans.

pares it with the variation shown in the number of intermediate ganglia in his embryos, which he found to be between three and seventeen, and suggests the difference in numbers may be purely accidental due to the great individual variation.

In the same paper, however, Wrete shows a profile reconstruction of

	10,3 mm l	10,3 mm r	15 mm l	15 mm r	15,4 mm l	15,4 mm r	21,1 mm l	21,1 mm r	22,3 mm l	22,3 mm r	25,2 mm l	25,2 mm r	27 mm l	27 mm r	29 mm l	29 mm r	39,6 mm l	39,6 mm r	41 mm l	41 mm r	65 mm l	65 mm r	77,5 mm l	77,5 mm r
C_1	–	–	•	•	•	•	•	•	• •	•			•	•			•				• •	• •		
C_2					–		+ • •	•	•	•		– •	• •	•	•	•	•	•	•	•			•	
C_3			•	+	• • •	– • •	• •	•	• •	•	•	• • •	•	•	•	•	•	•	•	•	•	•	•	+
C_4					•	• •	• •	•	•	• •	• • • •	•	•••••	• • • •			•	• • •	• +	• • •	• •	• • •	•	• +
C_5										•	•	•	+	•				•						
C_6							+	+					+	+							– + +	+ + +	+ + +	+ + + +
C_7					+	+	+	+												+				+
C_8																			–	+	–	+ +		–
Th_1			–	–	–	–				–									+ +	–				–
Th_2			–	–	–	–					– o								o				•	•
Th_3											–												+	
Th_4																						o		
Th_5																								
Th_6												–												
Th_7					o					o														
Th_8																								
Th_9																			+					
Th_{10}							+				–		–	+			+				+	+		
Th_{11}	–	–											–	+		–	–				+	+	+	
Th_{12}	–	–		–		o			–		o	–	+	+	•				•	•	+ +		+ + o	+ o
L_1	–	–	–	–	–	–			– +	– +		+ •	+ + +	– +			+	– + •	+	+ +	+ +	+ + +	• •	+ • •
L_2	–	–	–	–	–	–		– + o	–	– +	– •	– + +	+ +	–	•			– + •			– o o	++++	+ • • •	+
L_3	–	–	–	–	–	–	+	–	–	–	–	–	–	– +		–	+ + +	+	+		+ + + •	+	+••••	+ • •
L_4	–	–	–	–	–	–	+	–	–	– +			– +	–	–	–	+	–	–	–	– +	+	+	+
L_5	–	–	–	–	–	–		–	–	–	–	–	–	–	–	–	+ +		–	–	+	+		+
S_1	–	–	–	–	–	–					–	–	–	–							+		+	–
S_2											–	–												
S_3																								
S_4																								
S_5																								
Co_1																								

– cellular processes from paravertebral sympathetic chain
+ intermediate ganglion in or on a grey ramus communicans
● intermediate ganglion in or on a spinal nerve or spinal nerve branch
○ intermediate ganglion in or on a white ramus communicans.

Fig. 53 Occurrence of intermediate ganglia in human embryos according to Wrete. Wrete, M. (1941). *Z. mikr.-anat. Forsch.*

one side of a silver-impregnated human foetus of 81 mm. in which fourteen ganglia were present (Fig. 52). Also it may be seen from the table of his findings in twelve other human embryos and foetuses between 10 and 77 mm. (Fig. 53) that intermediate ganglia in the lumbar region of the two foetuses larger than 60 mm. are present on each side in sixteen, twelve, seventeen and twelve instances respectively.

It seems possible, therefore, that in Wrete's observations on adult subjects he may have missed finding the smaller ganglia because of their variable position. His method was to remove the lower thoracic and lumbar spine with the adjacent body wall and place it in 10 per cent. formalin. Then he dissected out the rami, ganglia and spinal nerves with the aid of a lens. This is certainly not so sure a method as had been adopted on the left side of the subject described here. In this respect it is interesting to recall Fagarasanu's report (1938) that he found intermediate ganglia in the lumbar region in no more than 50 per cent. of the cases he examined—not even in every case!

In reviewing the findings, therefore, the presence of eighteen and twenty intermediate ganglia on each side of the specimen described here does not indicate that they were abnormally frequent; indeed, the author believes that similar observations on adult material will be made in the future. The technique described here will produce the most accurate results, but it is very laborious and has entailed the preparation of over 6,000 sections and therefore can hardly be recommended as a routine method.

It is suggested instead that the examination of a number of human foetuses larger than 60 mm. will be a more convenient method of assessing the occurrence of intermediate sympathetic ganglia. Transverse serial sections will enable individual variations to be compared much more easily than the same number of dissections in adults and will also, in younger embryos, give information on their development.

Chapter 10

SWEATING IN THE PERINEUM

In the account of the observations on cases of lumbar and thoraco-lumbar sympathectomies examined in the earlier chapters, it was noted that sweating in the perineal area was constantly retained. Immediately after operation it appeared to be present deep in the natal cleft, and in the folds of the buttocks extending forwards on either sides of the scrotum or labia majora to the front of the perineum, and slightly forwards in the folds of the groin. A year or so after operation, however, this area of thermoregulatory sweating appeared to have extended slightly from the natal cleft an inch or two on the inner sides of the buttocks and rather more extensively in the folds of the buttocks. It also included the upper inch or two of the inner thigh, where it then became continuous with the sweating from the escape area on the front of the thigh in the L.1 and L.2 dermatomes. Although this area of sweating in the perineum was often continuous with the sweating in the escape area over the back of the sacrum, this was not always found, even at long intervals after operation. In these cases it was separated from the sweating in the escape area by a band of anhidrosis two inches or so wide.

This sweating in the perineum had been noted by other observers, but no acceptable explanation appears to have been made. In a discussion (Netsky and Walker with Richter, 1947*b*), it has been suggested that this low electrical resistance may be due to 'contact sweating', but Ray and Console (1948) show that this cannot be the whole reason since it persists when the skin of the scrotum is exposed to dry air. Also, the skin resistance can be raised on the sides of the scrotum, which are supplied by the ilio-inguinal nerves, by section of the T.12, L.1 and L.2, nerve roots thus dividing the preganglionic fibres to the relevant lumbar intermediate sympathetic ganglia. Ray and Console report that they were unable to reduce the skin resistance in this region by any other method—such as spinal anaesthesia to various levels, or by resection of all the sacral paravertebral sympathetic ganglia on one side. The author has made observations on cases of spinal anaesthesia (e.g. Case C.A.) and cases of paraplegia, in which all thermoregulatory sweating has been absent below the level of the lesions. In neither group of cases was the pattern much altered. The escape area disappeared, and the perineal sweating area became smaller in front and was confined to the borders of the fold of the groin. These observations may not give abso-

lute evidence, however, because local anaesthetic block and spinal anaesthetic block do not produce such a high level of resistance in the skin as is found in sympathetically denervated areas some time after the relevant nerve section. Probably this alteration in pattern is due to the fact that the skin still contains sufficient sweat in the sweat glands, though the pores of the latter are closed. Possibly, therefore, if this perineal skin were denervated for some days, it might then be found to have a high resistance indicating the removal of sudomotor fibres. Similarly, although after paraplegia the rest of the skin is dry and scaly, these patients are invariably incontinent and, therefore, again the skin here is kept moist. It is possible that cauda equina lesions may yield more information if cases can be found which have a watertight suprapubic drainage.

The whole aspect of sweating in the perineum must be considered in greater detail.

Cases of anterior rhizotomy of the lumbar and upper sacral nerve roots (Fig. 23) might have been expected to provide information on perineal sweating, but in these cases the nerve roots sectioned did not include the pelvic parasympathetic outflow (nervi erigentes). In all three cases studied by the author, however, the lower margin of sweating included the whole of the perineum. No case has been available on which, after preganglionic section of lumbosacral nerve roots, an area of sweating could be demonstrated that was localized to the perineum. Richter (1927) and more recently Wagner (1952) have confirmed the belief that electrical skin resistance is related to sweat gland activity rather than to the peripheral circulation. Wagner found that in individuals congenitally devoid of sweat glands, the electrical resistance corresponded to that of sympathectomized areas: relatively low skin resistance was present in the central part of the face and in the axilla. Unfortunately, he gives no information on the perineum and the author has had no opportunity of studying such a case.

Johnson *et al.* (1952*a* and *b*) have recently reported the finding of large areas of anhidrosis after anterolateral chordotomy performed in the T.1–T.2 segment of the cord. In these cases there was some dissociation of sweating and vasomotor patterns, but they found that in all cases in which there was loss of sweating the area of the central mask of the face, and of the perineum, always escaped. There was, of course, no escape area in the upper lumbar dermatomes. This interference with vasomotor and sudomotor pathways followed unilateral as well as bilateral chordotomy, but was never contralateral. The lesions in the cord were in the anterolateral quadrants and, as is usual, extended to a depth of 5–7 mm. There was no apparent injury to the pyramidal tracts, but complete absence of pain was produced.

The patterns of anhidrosis were never permanent but showed re-

covery with time. The observation of these workers, that the central mask of the face and the perineum were not involved in the anhidrosis, confirms the hypothesis that these areas are supplied with sudomotor fibres which originate other than in the preganglionic cell nuclei of the thoraco-lumbar outflow from the cord. There is, however, no indication as to where these cells may lie.

In order to consider more exactly the occurrence of this sweating in the perineum, it will be an advantage to examine other reports on the segmental dermatome value of this area. Unfortunately Foerster made no observations on the dermatomes below that of the second sacral. If the dermatome chart (Fig. 2) is re-examined, it will be noticed that on the back of the figure the upper medial edge of the S.2 dermatome is shown to extend from the upper two inches of the inner thigh towards the natal fold, and then up an inch or so from the mid-line of the natal cleft until it joins the L.3 dermatome on the upper buttock. As, according to Foerster, most of the dermatomes on the limb appear to overlap by at least one dermatome, it is suggested that this medial edge of the S.2 dermatome on the buttock may correspond closely to that of the outer edge of the S.4 dermatome. It will be evident that this edge follows very closely the area of sweating in the perineum—as has been found experimentally in the cases described here.

The dermatome chart of Head (Fig. 3) indicates a rather extensive S.3 dermatome and a small area for S.4 dermatome which is semicircular in shape on each side, and centred about the anus.

If Head's paper (1893) is examined more carefully, however, it will be seen that his information on the S.3 and S.4 dermatomes is based on very limited evidence. He had made only one personal observation and this was on a case upon which he had tested for pain in the skin following on a visceral injury. '. . . this pain represents the gluteo-perineal (3rd sacral) area . . . caused by the unfortunate removal of a piece of mucous membrane of the bladder during the crushing of a phosphatic calculus. . . . The shaded area represents the third and fourth sacral area.' His accompanying illustration (Head, *figure 33*) is shown in Fig. 54. Head notes that there is a small patch of skin at the base of the scrotum which is unaffected and that this patch is supplied from the 12th thoracic nerve. This observation fits in exactly with that of Ray and Console (1948).

Head's only other information on the extent of these dermatomes was obtained from von Bärensprung, who illustrated a case 'where the eruption [of herpes] almost exactly coincided with the two upper sacral areas . . . as . . . in *Fig. 33*' (presumably Head means S.3 and S.4). The distribution of the herpes in this case is shown in Fig. 55. It is evident that neither of these cases is able to provide exact information on the extent of either S.3 or S.4 dermatomes.

No other observation seems to have been recorded on man. Sherrington (1893) provides very relevant observations which he made on the macaque monkey. All told, he examined the residual sensibility of nerve roots in this area in six cases which included both sexes. Although the macaque has the same number of cervical and thoracic vertebrae as

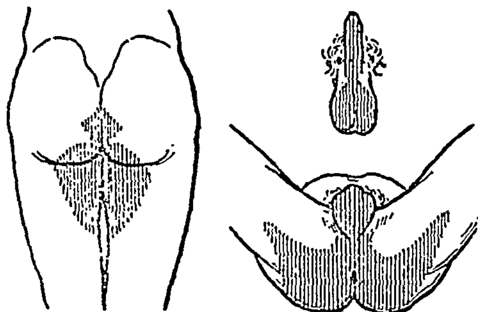


FIG. 54. To show the cutaneous tenderness in a bladder case. The shaded areas represent the 3rd and 4th sacral. Note that there is a small patch of skin at the base of the scrotum which is unaffected. This is supplied from the 12th dorsal. Head, H. (1893). *Brain.*

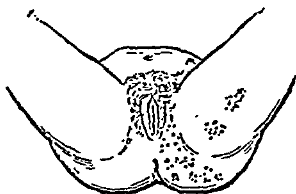


FIG. 55. To show the distribution in a case of herpetic eruption. (Copied from von Bärensprung.) Head, H. (1893). *Brain.*

has man, it has seven lumbar vertebrae and only three sacral. Sherrington numbered the nerve roots in relation to the lowest rib: the 9th post-thoracic nerve root therefore corresponds to the 4th sacral (S.4) in man. In considering the levels of the spinal reflexes (knee jerk) Sherrington considered that the L.2 root in the monkey corresponded to the L.1 root in man, and that the L.5 in the monkey corresponded to the L.4 in man, but later he stated that he believed that the 9th post-thoracic

covery with time. The observation of these workers, that the central mask of the face and the perineum were not involved in the anhidrosis, confirms the hypothesis that these areas are supplied with sudomotor fibres which originate other than in the preganglionic cell nuclei of the thoraco-lumbar outflow from the cord. There is, however, no indication as to where these cells may lie.

In order to consider more exactly the occurrence of this sweating in the perineum, it will be an advantage to examine other reports on the segmental dermatome value of this area. Unfortunately Foerster made no observations on the dermatomes below that of the second sacral. If the dermatome chart (Fig. 2) is re-examined, it will be noticed that on the back of the figure the upper medial edge of the S.2 dermatome is shown to extend from the upper two inches of the inner thigh towards the natal fold, and then up an inch or so from the mid-line of the natal cleft until it joins the L.3 dermatome on the upper buttock. As, according to Foerster, most of the dermatomes on the limb appear to overlap by at least one dermatome, it is suggested that this medial edge of the S.2 dermatome on the buttock may correspond closely to that of the outer edge of the S.4 dermatome. It will be evident that this edge follows very closely the area of sweating in the perineum—as has been found experimentally in the cases described here.

The dermatome chart of Head (Fig. 3) indicates a rather extensive S.3 dermatome and a small area for S.4 dermatome which is semicircular in shape on each side, and centred about the anus.

If Head's paper (1893) is examined more carefully, however, it will be seen that his information on the S.3 and S.4 dermatomes is based on very limited evidence. He had made only one personal observation and this was on a case upon which he had tested for pain in the skin following on a visceral injury. '. . . this pain represents the gluteo-perineal (3rd sacral) area . . . caused by the unfortunate removal of a piece of mucous membrane of the bladder during the crushing of a phosphatic calculus. . . . The shaded area represents the third and fourth sacral area.' His accompanying illustration (Head, *figure 33*) is shown in Fig. 54. Head notes that there is a small patch of skin at the base of the scrotum which is unaffected and that this patch is supplied from the 12th thoracic nerve. This observation fits in exactly with that of Ray and Console (1948).

Head's only other information on the extent of these dermatomes was obtained from von Bärensprung, who illustrated a case 'where the eruption [of herpes] almost exactly coincided with the two upper sacral areas . . . as . . . in *Fig. 33*' (presumably Head means S.3 and S.4). The distribution of the herpes in this case is shown in Fig. 55. It is evident that neither of these cases is able to provide exact information on the extent of either S.3 or S.4 dermatomes.

The close correspondence between these patterns observed in the macaque and the information which is known to be relevant in man would seem to suggest that the area in which sweating is retained in the perineum almost exactly corresponds to that of the S.4 dermatome, and possibly S.5 is included.

It should be remembered that the pelvic outflow of the parasympathetic system is from the S.2, S.3 and possibly S.4 roots. These contain many fine myelinated fibres of a diameter comparable to some found in the 3rd, 7th, 9th and 10th cranial nerves. A possible suggestion, therefore, could be that there was an alternative sudomotor pathway to the perineal skin via this pelvic parasympathetic outflow (nervi



Fig. 58. Female macaque. To show extent of 9th post-costal dermatome. Sherrington, C. S. (1893). *Phil. Trans. B.*

erigentes). This is distributed to the pelvic contents and to the blood vessels of the erectile tissue. This outflow is always present in the S.3 nerve root and may be found also in S.2 or S.4 or both—probably depending on the relative level of fixation of the sacral plexus. If some of these fine myelinated autonomic nerves were sudomotor in function we should expect sweating also in the S.3 dermatome, but it is evident that the area of [illegible]

[illegible]

[illegible] spectra of the anterior nerve roots.

Unfortunately, very little information is available on this subject in man. Pick and Sheehan (1946) have counted the numbers of small myelinated fibres and found that the upper and lower edges of the thoraco-lumbar outflow were blurred and that all the cervical anterior

of the monkey (S.2) had relatively the same segmental value as the 9th post-thoracic (S.4) in man. The patterns which Sherrington delimited for the 9th post-thoracic dermatome are shown in Figs. 56, 57 and 58.

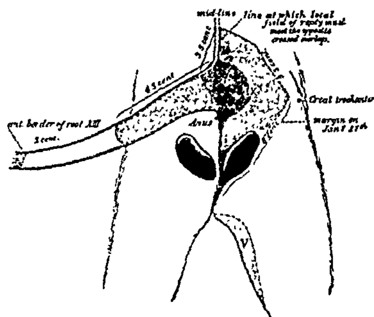


Fig. 56. Male macaque. To show extent of 9th post-costal dermatome. Sherrington, C. S. (1893). *Phil. Trans. B.*

It will be apparent that the distribution of this dermatome almost exactly corresponds to the area in man where sweating occurs in the perineum after lumbar sympathectomy. In the male, the area indicated by Sherrington extends up towards the sacral spines, then rather more laterally towards the greater trochanter than is found in man, and then forwards again between the folds of the buttock and in the perineum, but does not include the sides of the scrotum nor, apparently, the dorsum of the penis. Sherrington observes that the innervation of the side of the scrotum was from the 1st lumbar nerve which corresponds closely to Ray and Console's indication that sudomotor fibres to the sides of the scrotum were supplied by the ilio-inguinal nerve in man. After lumbar sympathectomy in man, of course, this area on the sides of the scrotum and also possibly on the dorsum of the penis is supplied by the intermediate ganglia of the upper lumbar nerve roots. Sherrington's pattern for the supply in the female macaque is similar to that of the male, and again extends rather more laterally towards the greater trochanter than it does in the human.

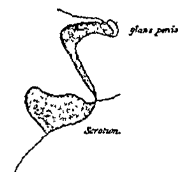


Fig. 57. Male macaque. 9th post-costal dermatome, as above. Sherrington, C. S. (1893). *Phil. Trans. B.*

nerve roots contained at least a few such fibres, never exceeding 100 in those above the 7th cervical. Similar fibres were also present in the lower lumbar and upper sacral nerve roots. Unfortunately, these workers only counted the number of fibres in a few selected nerve roots, and the information they gave is therefore too incomplete to be of any real service in the present argument.

The only information on the sizes and percentages of the fibres in the anterior nerve roots in man is given by Swensson (1938) in otherwise unpublished data which is quoted by Rexed (1944). Table VI was prepared from Dr Swensson's original notes. These fibres were measured on one side only in an adult aged thirty years. The peaks of the greatest frequency of a particular diameter of nerve fibre are shown in heavy type. It will be seen that the thoraco-lumbar outflow in this case extended from T.1–L.1 inclusive, and that below this level only a few fine myelinated fibres were present. Indeed, the S.2 and S.3 contained only a very small proportion of such fibres. The S.4 anterior nerve root, however, suddenly showed a large number of fine fibres—21·7 per cent. were 2μ–3μ, and 17·2 per cent. were 3μ–4μ in diameter. This information is confirmed by data from a new-born child which Rexed himself had measured (Tables VII and VIII). Again we see a sudden efflux of fine myelinated fibres at the S.4 level—38·5 per cent. were 1μ–2μ and 34·2 per cent. were 2μ–3μ in diameter. In other cases which Rexed included in his paper, but not examined in full here, he found an outflow of fine fibres at S.4 most commonly, although it may also appear at S.3. Unfortunately, the relative diameters of the fibres cannot be compared, as his subjects are all of different ages, and mostly very young. The relative levels are still indicative of the levels of outflow of fine myelinated fibres. Although Rexed does not appear to consider the point, it would seem that the so-called pelvic splanchnics (nervi erigentes) are really not such fine fibres as had been thought. The original observations on this point were made by Gaskell in 1886. His observations, however, were made only upon two collie dogs, and there seems to have been little confirmatory work on this aspect made since. In any event there is an outflow of fine myelinated fibres of a similar diameter to the thoraco-lumbar outflow which leaves the sacral cord via the S.4 root. This is the same dermatome that shows residual sweating in the perineum after thoraco-lumbar sympathectomy. The author therefore suggests that although some of these fibres may be distributed to the blood vessels of the urinogenital apparatus, some are preganglionic fibres to sweat glands in the perineum. The site of the postganglionic cells must remain a subject for speculation. The connections of the nerve fibres in this region are most complicated, and ganglion cells abound in the pelvic plexus. It will be most difficult to follow the route of such an alternative pathway by anatomical methods, but perhaps this can be

Table VI.

Segment	1—2μ	2—3μ	3—4μ	4—5μ	5—6μ	6—7μ	7—8μ	8—9μ	9—10μ	10—11μ	11—12μ	12—13μ	13—14μ	14—15μ	15—16μ
C 1	3·0	12·3	11·2	15·2	5·9	7·3	6·6	15·2	12·1	7·3	2·8	0·9			
C 5	1·5	7·6	8·5	5·8	6·7	7·9	9·4	18·1	15·9	14·7	2·2	1·5	0·6		
C 6	5·6	7·9	9·8	9·6	5·4	10·6	17·6	22·4	8·4	2·1					
C 7	1·8	7·3	8·2	6·3	2·1	6·3	8·9	14·8	20·0	14·8	5·4	2·6	0·7		
C 8	0·7	7·2	10·2	7·7	6·1	16·1	18·9	25·7	4·8	2·1	0·2				
Th 1	12·2	26·2	6·4	4·8	2·6	2·8	8·0	22·2	9·1	3·3	1·5				
Th 2	15·2	43·6	10·3	4·5	1·4	2·2	2·7	9·8	4·5	3·3	1·5	0·6	0·3		
Th 3	20·7	51·5	2·7	1·7	0·4	3·7	3·6	10·7	3·6	1·1					
Th 4	20·6	49·2	5·4	2·0	1·1	3·6	4·9	9·8	2·0	1·1					
Th 5	19·2	49·3	4·1	1·8	2·5	5·5	5·5	9·2	1·7	0·9					
Th 6	19·7	49·1	7·3	2·1	1·5	2·6	5·4	10·1	1·2	0·3	0·3				
Th 7	14·2	50·3	5·1	1·8	0·6	5·7	9·0	10·0	2·4	0·6					
Th 8	18·0	50·8	3·8	1·6	2·2	4·9	5·7	10·3	1·8	0·5					
Th 9	16·1	43·8	6·6	4·7	0·6	3·0	5·1	10·9	5·1	3·0	0·8				
Th 10	14·7	46·7	10·3	4·7	1·8	3·7	4·5	10·7	1·9	0·5	0·2				
Th 11	18·8	48·6	8·8	3·1	1·1	0·8	1·1	7·1	3·1	4·2	3·5				
Th 12	18·0	53·4	13·8	2·7	0·4	1·8	2·0	4·2	3·1	1·3	0·4				
L 1	9·0	26·3	15·7	7·2	2·8	8·7	7·4	16·5	4·1	2·1	0·3				
L 2	2·9	9·2	9·4	9·0	5·0	5·9	3·3	12·9	14·9	15·9	5·8	4·8	1·4		
L 3	1·4	4·1	8·7	6·2	3·8	5·4	9·1	24·9	25·9	7·3	2·7	0·3			
L 4	1·0	7·9	9·2	4·8	4·1	2·7	8·5	32·3	20·2	8·2	0·7				
L 5	2·5	6·0	4·2	5·5	2·7	7·3	8·8	22·2	18·4	15·6	4·8	3·0	0·3		
S 1	—	1·3	6·3	2·7	2·7	3·6	3·6	11·3	14·7	25·9	15·6	9·3	1·9	0·3	0·3
S 2	—	1·3	2·7	0·7	0·7	4·4	7·1	22·3	25·0	27·5	5·4	3·4			
S 3	—	0·9	2·9	1·3	2·6	6·9	4·2	15·8	23·4	29·4	9·9	1·9	0·3		
S 4	4·9	21·7	17·2	5·6	3·9	3·4	4·5	12·5	10·3	10·9	2·8	1·5	0·4		

Table showing the calibre spectra of the ventral spinal nerve roots in a man aged 30. The case was investigated and published in diagrammatical form by Swensson (1938). The table was compiled from Dr Swensson's original notes. (From Rexed, B. (1944). *Acta psychiat. (Kbh.)*)

These two experiments would appear to confirm the existence of vasoconstrictor nerves to the limb vessels in the pelvic outflow of the cord.

Häggqvist (1937), in an analysis of the fibre spectrum of anterior roots in the macaque, showed that in the sacral region there is a peak

Table VIII.

Segment	1–2μ	2–3μ	3–4μ	4–5μ	5–6μ	6–7μ	7–8μ	8–9μ
C 1	15·5	29·9	14·4	23·6	10·2	6·0	0·4	
C 2	26·8	31·0	18·7	18·7	3·9	0·7	0·4	
C 3	14·3	34·5	22·9	22·1	3·9	1·9	0·4	
C 4	9·5	19·1	24·4	26·0	13·2	6·9	1·0	
C 5	6·7	19·3	23·5	28·8	14·4	6·7	0·4	0·4
C 6	5·4	16·1	20·5	33·3	16·1	8·3	0·3	
C 7	4·4	13·8	28·9	35·7	11·8	3·7	0·7	
C 8	6·9	19·4	21·5	34·7	11·5	5·6	0·3	
Th 1	7·5	21·0	24·9	33·1	10·5	4·9		
Th 2	13·3	24·2	27·2	25·8	7·5	0·2		
Th 3	6·8	16·0	30·0	28·7	13·9	4·2	0·4	
Th 4	3·3	15·9	33·6	29·7	10·0	4·5		
Th 5	2·8	17·3	39·1	30·3	9·2	1·1	0·4	
Th 6	2·7	18·0	36·0	32·6	10·3	0·4		
Th 7	1·8	15·4	33·1	34·6	11·8	2·9	0·4	
Th 8	5·9	17·4	37·4	29·1	8·5	1·8		
Th 9	3·6	16·5	24·6	30·8	17·1	7·2	0·3	
Th 10	6·2	11·8	19·6	33·6	19·9	7·5	0·3	
Th 11	6·4	8·9	22·4	32·6	20·7	8·6	0·7	
Th 12	7·9	12·6	27·3	33·1	14·7	4·1	0·4	
L 1	7·7	13·2	16·1	17·3	21·1	15·3	6·7	3·1
L 2	4·4	15·4	15·1	25·4	21·3	13·8	3·4	1·3
L 3	6·5	11·0	17·8	30·1	20·4	11·7	1·9	0·6
L 4	3·8	14·0	17·1	23·6	18·2	16·4	5·5	1·4
L 5	6·8	10·2	18·4	24·7	22·0	13·7	2·9	1·3
S 1	3·6	17·1	19·0	24·6	19·4	14·4	2·0	
S 2	16·9	29·0	19·9	18·2	11·1	3·6	1·0	0·3
S 3	4·3	18·4	30·0	29·0	14·5	3·4	0·5	
S 4	38·5	34·2	16·1	8·0	2·0	1·3		
S 5	24·6	36·8	26·4	10·0	1·4	0·5		0·5

Table showing the calibre spectra of the ventral spinal nerve roots in the new-born. (From Rexed, B. (1944). *Acta psychiat. (Kbh.)*)

outflow of small myelinated fibres at S.1 level (corresponding to S.3 in man) and, below this, a further outflow with peak at Co.1 (corresponding to what would be the coccygeal nerve root in man). It would appear therefore that, in man, this second outflow has been condensed upwards toward that of th

of the caudal vertebrae.

achieved by experimental methods. Indeed, such experiments already have furnished the indications that such an outflow exists.

When anterior nerve roots in the lumbo-sacral area have been sectioned at operation, the author has taken the opportunity of observing the effects of electrical stimulation of the nerve roots exposed intradurally. Plethysmograph cups have been fixed to the patient's great toes, and a catheter, with manometer attached, inserted into the bladder. On the last two cases which have been examined in this way, vasoconstriction has been observed on stimulating the T.12 and L.1

Table VII.

Nerve	1–2μ	2–3μ	3–4μ	4–5μ	5–6μ	6–7μ	7–8μ	8–9μ
N. III . .	11·8	14·6	15·5	24·4	24·6	8·9	0·3	
N. IV . .	6·5	18·6	25·5	36·8	10·2	1·9	0·6	
N. V . . (motor root)	2·2	13·0	19·9	37·6	22·1	4·4	0·6	
N. V . . (sensory root)	39·9	39·9	17·1	2·8	0·3			
N. VI . .	5·4	9·9	13·4	44·5	21·6	4·5	0·6	
N. VII . .	7·0	27·1	32·8	28·1	4·2	0·7		
N. VIII . (cochlear nerve)	33·8	46·0	14·6	5·6				
N. VIII . (vestibular nerve)	13·0	36·5	25·4	15·9	6·4	2·2	0·6	
N. IX . .	45·0	39·4	12·9	2·8				
N. X . .	8·9	37·6	26·3	20·2	6·0	0·9		
N. XI . .	6·6	21·0	14·4	32·4	23·0	2·6		
N. XII . .	4·1	27·7	30·1	31·3	6·5	0·3		

Table showing the calibre spectra of the cranial nerves in the new-born.
(From Rexed, B. (1944). *Acta psychiat. (Kbh.)*)

anterior nerve roots. Ordinary motor activity was produced on stimulating all the lumbar and upper two or three sacral anterior roots. Stimulation of the S.2 anterior root produced contraction of the bladder, and this was usually more marked on stimulating S.3. In one case the level of this parasympathetic outflow was asymmetrical and no bladder contraction was produced at S.2. On every occasion that contraction was produced in the bladder, vasoconstriction was also evident in the toe. This was shown by a transient decrease in volume of the toe and decrease in the pulse wave lasting a few seconds. The S.4 root was not accessible. Some support for these stimulation experiments has been provided by Scheibert (1955), but he does not specify the sacral levels stimulated.

Chapter 11

§1. SWEATING IN THE CENTRAL MASK OF THE FACE

It will be seen from the sweating patterns illustrated in Figs. 17–21, that in all 10 cases (18 sides) examined *shortly* after cervico-dorsal sympathectomy, sweating was present in the central mask of the face. In 15 of these sides, Horner's syndrome or partial Horner's syndrome was also present, but it was absent in the 3 sides on which the stellate ganglion had not been resected. Although sweating in the central area of the face was present in all cases, sweating over the larynx was certainly present as a localized area only on 10 relevant sides and absent on 4 sides, and sweating in and around and behind the external auditory meatus was certainly present on 7 sides and absent on 9.

It would appear that there is an alternative sudomotor pathway invariably present to the central mask of the face, and occasionally present to the skin over the larynx and around the external auditory meati.

That this area of low electrical resistance is really due to sweating may be seen from the illustrations Fig. 62 (*a–h*) and from reports of other observers which have been illustrated by photographs in their texts. These will be discussed in detail later.

Richter (1947*a*) in a paper describing the patterns of a low electrical skin resistance in cases of cervico-dorsal ganglionectomy, has illustrated patterns very similar to those shown in Figs. 17–21. On *page 224* of his paper he stated that in most individuals after upper thoracic sympathectomies, he found that the central portions of the face had a lower skin resistance. He illustrated patterns obtained after 'Smithwick' types of 'preganglionic' sections of T.2 and T.3 ganglia. These patterns are very similar to those shown here, except that they do not extend so high onto the forehead. In two other cases which he stated had undergone a 'preganglionic' section of T.2 and T.3 ganglia he showed a pattern extending to include the whole forehead, and another which extends down over the chin to include the skin over the larynx. A fourth pattern, which included the area around the nose and mouth only, he stated he observed after a case of stellate ganglionectomy.

Richter considered that these regions corresponded closely to those areas of low resistance in normal individuals—which he had described with Woodruff (1942). These areas decreased in the cold and during sleep to a narrow band around the mouth, and expanded during heat

There is no reason to suppose that an outflow of 'sympathetic' (sudomotor) nerves may not have been concealed in the pelvic 'parasympathetic' outflow. This hypothesis is attractive but may be difficult to prove. It is further strengthened by consideration of the possible alternative pathway to the sweating area of the central mask of the face. This will be considered in the next chapter.

It might be argued that if such a sympathetic sudomotor outflow exists at the S.4 nerve root, then, after paravertebral lumbar or thoraco-lumbar sympathectomy, would not these preganglionic fibres establish functional connection with the ganglion cells in the sacral area which had been deprived of their preganglionic connections by the sympathectomy? There is no immediate explanation for this absence of sweating in the upper sacral dermatomes, but it does not appear to occur.

Over the course of time the area of sweating in the perineum extends only very slightly towards the buttocks. Possibly the preganglionic fibres leaving in the S.4 root have such a limited distribution to post-ganglionic cells in this region that they are not able to establish functional connections with those cells in the paravertebral sympathetic chain in the upper sacral region, which would have supplied the S.3 and S.2 dermatomes. This hypothesis merits further investigation and, now that the possibility is recognized, further experimental work may be planned with a view to establishing its validity.

GENERAL CONCLUSIONS

After thoraco-lumbar and lumbar sympathectomy sweating activity is invariably retained in the perineum in the S.4 and S.5 dermatomes. Although no particular nerve section has provided absolute evidence that this sweating is effected by nervous pathways, it is believed that this is the probable manner by which it is produced. Sweating on the sides of the scrotum can be abolished by section of the ilio-inguinal nerve.

It is suggested that sudomotor fibres leave the lower sacral cord. These fibres may be included with those of the sacral outflow of the parasympathetic nervous system, or of a cholinergic outflow of the sympathetic which is closely associated with it, and is probably present in the S.4 anterior nerve root.

the smooth muscles of the eye and the upper eyelid are indicated by a dotted line.

A similar diagram has been used by Guttmann and List (1928) and shows their conception of the sympathetic and accessory sudomotor pathways. Their illustration has been redrawn and is shown here in Fig. 60.

The postganglionic fibres from the superior cervical ganglion are indicated as a strong continuous line; the sensory innervation from the face passing to the cells in the trigeminal ganglion is indicated by a fine interrupted line; the postulated pathway of accessory fibres from cells contained in a nucleus in the medulla is indicated by a dotted line. It is closely associated with the sensory fibres. These two illustrations give a good indication of the complexity of the nerves to the skin of the face.

It will be an advantage to examine the illustrations and case reports of Guttmann and List's paper in greater detail. Their *figures 12 and 13* indicate that lesions of the sympathetic cause general anhidrosis of the face except around the orbit, side of the nose, and the upper and lower lips—that is, in the central mask area. In these areas, however, an injection of pilocarpine produces sweating before that on the intact opposite side. Similarly they illustrate a case (*their figure 14*) of gustatory sweating following on a sympathetic lesion in which the origin was not precise. Although on heating this patient there was relative anhidrosis of the face on the injured side, except on the upper lip, both swallowing vinegar and the early effects of a pilocarpine injection caused increased sweating on the affected side of the face. In another case (*their figure 15*) they showed that after facial palsy due to an intrapetrous lesion, but without any lesion of the cervical sympathetic, there was diminished sweating over the whole of that side of the face. From a study of these and other cases they concluded that lesions of the cervical sympathetic evidently could not prevent all facial sweating, especially in the central part of the face, and that in a case of gustatory sweating the afferent arc of the reflex might pass via the VII cranial nerve. They also showed that a lesion of the VII nerve caused diminished sweating on the face. They therefore thought that there must be two sets of sudomotor fibres and that the accessory set was most likely to pass with the facial nerve.

Guttmann (1931) produced more cases in support of his hypothesis, and certain of these are relevant here. *His figures 15 and 27* confirm that after peripheral section of the supraorbital nerve, complete anhidrosis results in the corresponding area. *His figures 23–26* confirm that sweating on the face is diminished after lesions of the facial nerve. In one of these cases gustatory sweating became evident as the facial palsy recovered. In another case apparently complete thermoregulatory anhidrosis of the face and neck was produced on one side, after a combined superior, middle and inferior cervical ganglionectomy and carotid neurectomy. Presumably the facial nerve was intact in this case (*his figure 19*) and

and excitement to include the whole of the face and part of the neck. The author's conclusions do not entirely agree with those of Richter in regard to the type of residual sweating to be found after different types of sympathectomy, and he believes that the variation is probably an individual one. The patterns, however, mutually confirm each other and also that the pattern over the skin of the larynx is not found on all occasions. Richter seems to have made no observations in regard to sweating around the external auditory meatus. The author's conclusions on this subject were given in a communication (Monro, 1950*b*).

In Case B.E. (Fig. 18) it has been shown that the area of sweating in the skin over the larynx is under nervous control and could be prevented by local anaesthetic block. Although various attempts have been made to find cases which show absolute anhidrosis in the central mask of the face, no suitable case has yet been available to the author. Various authorities, however, have given evidence that section or anaesthetic block of the supraorbital and infraorbital nerves will produce complete anhidrosis in the area of sensory loss. This has been well shown by Guttmann and List (1928). This type of nerve section will, of course, block the ordinary sudomotor fibres from the cervical sympathetic chain and also those of any alternative sudomotor pathway. Cases who have undergone intra-cerebral section of the nerves V, VII and IX alone, show no anhidrosis on the face. In none of these cases, however, has a cervico-dorsal sympathectomy also been performed, and it would appear to be necessary to perform a combination of sympathectomy and a cranial nerve section. This conclusion was also that of Guttmann and List, and from their observations they suggested that there was a double innervation of facial sweat glands by way of efferents from the facial nerve which join branches of the trigeminal just within or outside the skull. It now appears that this original hypothesis should be re-examined.

Lewis (1938—*page 330*) reported one case in which gustatory sweating developed in the centre part of the face after cervico-dorsal sympathectomy of T.2 and T.3 ganglia.

List and Peet (1938*d*), in their authoritative paper on sweat secretion from the face and its disturbances, confirm many of the findings of Guttmann and List. They refrain, however, from postulating any definite alternative pathway—such as by the facial nerve—although it is evident from their observations that the occurrence of facial sweating cannot be entirely explained on the basis of sudomotor fibres from the superior cervical ganglion. They consider the anatomy in detail, and their illustration of the principal autonomic pathways via the cranial nerves has been redrawn and is illustrated in Fig. 59. The pathways for sudomotor postganglionic fibres are shown as a continuous line. List and Peet, however, believe that the evidence for such fibres in the carotico-tympanic nerve is only doubtful. The oculo-pupillary fibres controlling

¶ Section of sensory root of trigeminal nerve or trigeminal ganglionectomy produces no area of anhidrosis although slight hypohidrosis may be seen in the temporal and frontal areas which, however, are only transient.

¶ Section of the peripheral branches of the trigeminal produces an absolute anhidrosis in the same area as the analgesia. They suggest that fibres probably from the internal carotid plexus enter the ophthalmic nerve intracranially, but that those to the maxillary and mandibu-

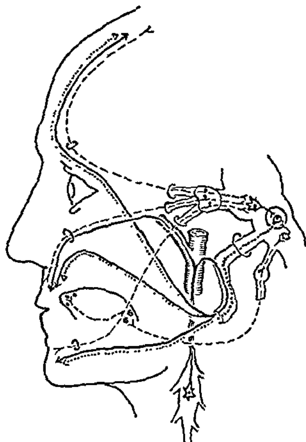


Fig 60. Course of sweating fibres to face (continuous line). Postulated pathway for accessory autonomic fibres (dotted line). Sensory fibres in nerves V and IX (interrupted line). Redrawn from Guttmann, L., and List, C. F. (1928). *Z. ges. Neurol. Psychiat.*

lar divisions join extracranially from the external carotid plexus, though some, perhaps, run from the deep petrosal nerve and the tympanic plexus (Fig. 59). It should be observed, however, that alcoholic injection into the foramen rotundum still leaves slight sweating on the upper lip and side of nose and lower eyelid, but procaine block of the infraorbital nerve prevents all sweating. See List and Peet, *figures 4B and C.*

¶ Intracranial section of the facial nerve causes no area of anhidrosis. A lesion near the geniculate ganglion, however, will cause a slight hyperhidrosis, but distal to the geniculate ganglion there is no

later gustatory sweating became evident around the lips and orbit. After an injection of pilocarpine, however, sweating was seen first in this area as usual (*page 23*).

Although Guttmann made observations on other areas of the body he does not seem to have noted sweating in the perineum—presumably

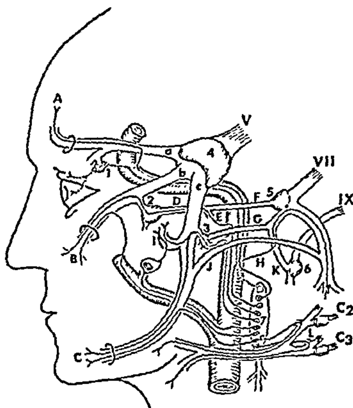


FIG. 59. Course of sweating fibres to the face (oculo-pupillary fibres are shown as a dotted line). Redrawn from List, C. F., and Peet, M. M. (1938). *Arch. Neurol. Psychiat. (Chicago.)*

1 Ciliary ganglion
2 Sphenopalatine ganglion
3 Otic ganglion
4 Trigeminal ganglion
a. ophthalmic
b. maxillary
c. mandibular
5 Geniculate ganglion
6 Petrous ganglion
7 Superior cervical ganglion

A Supraorbital nerve
B. Infraorbital nerve
C. Mental nerve
D. Nerve of pterygoid canal
E. Deep petrosal nerve
F. Greater superficial petrosal nerve
G. Lesser superficial petrosal nerve
H. Caroticotympanic nerve
I. Auriculotemporal nerve
J. Chorda tympani nerve
K. Tympanic branch of glossopharyngeal nerve
L. Cervical plexus

this was due to the absence of any cases of thoraco-lumbar sympathectomy, which would have allowed it to have become evident.

List and Peet (1938*d*) offer much clinical information in regard to facial sweating after single and combined lesions of different nerves. Like Guttmann's, all their cases were tested by Minor's starch-iodine method. Their observations and conclusions may be summarized thus:

GENERAL CONCLUSIONS

It is evident that the observations of earlier workers have been confirmed by the author and that even though no adequate explanation has been generally accepted, resection of the stellate ganglion or portions of the cervical sympathetic chain still allows sweating to be retained in the centre part of the face. There are, however, two other conditions—gustatory sweating and the auriculotemporal syndrome—which are concerned with abnomal sweating on the face and which merit further consideration.

§2. DEVELOPMENT OF CERTAIN NERVES OF THE FACE

It may be advantageous to consider here how the developmental history of the face and neck can contribute any information on its innervation. The fronto-nasal process and the maxillary processes fuse to form that part of the face above the mouth. The remaining part of the first branchial arch mesoderm of each side becomes the corresponding mandibular process, which soon fuses with its fellow in the middle line. Initially the more caudal branchial arches do not so fuse, and as they are also not as extensive laterally as the mandibular arch, a depression known as the cervical sinus is found on each side of the developing neck. This cervical sinus is bounded above by the mandibular arches, dorsally by the mass of somite mesoderm, and caudally by the developing pericardium. In the depression there can be seen the elevations of the 2nd, 3rd and 4th branchial arches. In some lower mammals it is considered that the cervical sinus is eventually covered over by a backward growth of the 2nd branchial arch.

Frazer (1927), however, showed that in man this is not precisely the case, and that the ectodermal groove between the 1st and 2nd arches—that is, the 1st branchial cleft—becomes obliterated except in its most dorsal portion in the region of the external auditory meatus. Behind this 2nd arch the details of the obliteration of the sinus are obscure. However, Frazer has demonstrated that the 3rd arch is not completely covered over during the disappearance of the sinus, but that, in part, it remains on the surface of the neck, as may be seen in the illustration (Fig. 61) taken from his paper. Closely related to the ectoderm covering the 3rd arch is the so-called epibranchial placode associated with the IX cranial nerve. Another placode originally derived from the 4th arch and associated with the X cranial nerve comes to lie on the caudal edge of the 3rd arch due to the relative reduction in size of the 4th arch. These placodes become attached to their corresponding nerves, and during

change in sweating. Middle ear disease may cause hypohidrosis probably because of involvement of the carotid plexus.

¶ Section of the sensory root of the trigeminal, the greater superficial petrosal, and the root of the glossopharyngeal nerves leads to slight hypohidrosis of the upper lip and cheek and temple.

¶ Malignant parotid tumour involving bone of the middle cranial fossa caused absolute anhidrosis including the lips, cheek, side of nose and lower eyelid.

¶ Resection of the superior cervical ganglia. List and Peet do not say at what interval their case was examined after operation although they state that anhidrosis was produced. It is evident, however, that some sweating is present on the upper lip.

CONCLUSIONS

Although a malignant tumour cannot be considered as necessarily producing a precise lesion, the general conclusion to be made from all these observations is that a peripheral lesion of a nerve to the face will produce complete anhidrosis, whereas lesions of the sympathetic in the neck or of certain cranial nerves produce only relative or incomplete hypohidrosis. A lesion in the region of the base of the skull must involve both systems, and again produces complete anhidrosis. Simonton and Gay (1948) provide further evidence of the dissociation of the autonomic supply to the upper face. They describe a case of apical petrositis in which anhidrosis was present only in the supraorbital region with myosis but no ptosis.

Further evidence of the persistence of sweating in the central mask of the face has been given by Guttmann (1940*a*). He illustrated a case after superior cervical ganglionectomy and described complete anhidrosis of the face resulting from this operation when examined four weeks after operation. His illustration, however (*figure 2*), shows that the mask of central sweating still persists. He described other cases of combinations of superior and middle cervical ganglionectomy, with and without stripping of the carotid artery, and of superior, middle and inferior cervical ganglionectomies. Although no comment is made on sweating in the face, a little can be seen here in the centre part in the figures! Guttmann went on to consider the phenomenon of 'perilesionary' hyperhidrosis which develops around an anhidrotic area and shows considerable activity after a few days. He states that this may be equal on the two sides, or increased on the ipsilateral, or increased on the contralateral border zone of the anhidrotic area. He believed that this reaction might be responsible for some of the abnormal areas of sweating and that it was probably a spinal or supraspinal reflex.

The fate of these placodes or vesicles has been considered further by Wilson (1955) when he considered the developmental origin of branchial cysts and fistulae. He showed that theoretically there could be a fistula associated with the endodermal pouches 1, 2 and 3. Rarely a first ectodermal cleft fistula may be found below and behind the ear, and connected with the naso-pharynx. Much more commonly a second cleft fistula may open into the pharynx in the region of the tonsil, but a complete third cleft fistula has never been described. Wilson pointed out that in all cases the development of the musculature of the tongue and its innervation from the hypoglossal nerve would cause these fistulae to course rostral to the hypoglossal nerve. Any connection there might be therefore between the skin over the larynx and the larynx itself (where there may occasionally be found an endodermally-lined diverticulum—presumably from the 3rd endodermal pouch) must also pass above the hypoglossal nerve.

It has been realized for many years that the ganglia associated with the V, VII, IX and X cranial nerves derive their cells partly from the neural crest but also from their associated epibranchial placodes—see Hamilton, Boyd and Mossman (1952—*pages 310–311*).

The matter has been investigated more closely by Batten (1956), who pointed out that in fish and amphibians the neural crest rudiment of the mixed cranial nerves is augmented by cells proliferated from certain placodal thickenings of the ectoderm and that these may furnish distinct lateralis and gustatory ganglia. In considering the fate of the epibranchial placode of the vagus in the sheep Batten (1957*b*) showed that intermittent streams of cells passed towards the nodose ganglion of the vagus and thought that the majority differentiated into neuroblasts. He was tempted, from conditions in lower forms, to assume that these placodal neuroblasts may relate to gustatory sensation. In his earlier communication he showed that cells from the appropriate placodes would pass into the petrous ganglion of the glossopharyngeal and the geniculate ganglion of the facial nerve. In another paper (1957*a*) Batten found that the maxillo-mandibular portion of the trigeminal ganglion arises principally from the neural crest associated with the V cranial nerve, but receives a limited contribution from its placode. The ophthalmic lobe of the ganglion has a dual origin, but the placodal contribution is significantly greater. Hamilton, Boyd and Mossman record that the ganglion cells related to this ophthalmic portion of the trigeminal ganglion, or profundus ganglion of lower forms, is distributed to the eye and the fronto-nasal process.

The origins of the cells which contribute to the cranial autonomic ganglia is still controversial, but Cowgill and Windle (1942) have studied this problem in the cat. They found that cells to the ciliary ganglion migrate along the ophthalmic nerve from the ophthalmic

subsequent development not only contribute cells to the trunk ganglia of these nerves but also gradually separate from the surface. This separation involves the initial formation of a tube-like process from each placode. Later the depths of the tube are completely separated off from the surface to form small vesicles in the depths of the neck. These are found for quite long periods of development attached to the ganglia of the IX and X cranial nerves.

Frazer was struck by the fact that the areas of skin initially related to these placodes, and which are part of the surface ectoderm of the 3rd and 4th arches, are not separated from the surface in subsequent development. He drew attention to the fact that the resulting skin pattern



FIG. 61. Development of dermatomes in the neck region. Frazer, J. E. (1927). *J. Anat. (Lond.)*.

was almost identical with that shown by Head (1894—*page 426*) as being that which represented the cutaneous area associated with the superior laryngeal nerve. Head had observed tenderness here in a case of tuberculosis of the upper part of the larynx affecting mainly the epiglottic and aryteno-epiglottic folds.

Frazer's observations have been confirmed by Garrett (1948), who traced the formation of the cervical vesicles from the depths of the ectodermal branchial clefts and showed that they separated from the ectoderm before they eventually disappeared. He showed that in later development the 4th branchial arch becomes relatively much reduced, so that there was little separation between the 3rd and 4th clefts. The contribution of the placode to the ganglion of the X cranial nerve was always more conspicuous than that of the more rostral placode of the IX.

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part of the trigeminal ganglion. Cells to the sphenopalatine ganglion came from both the trigeminal, via the maxillary nerve, and the geniculate ganglion via the greater superficial petrosal nerve (VII). Cells to the submandibular ganglion were derived from the trigeminal ganglion via the lingual nerve. Cells to the otic ganglion came from the trigeminal and a few from the petrous (IX) ganglia via the mandibular and the lesser superficial petrosal nerves respectively (Fig. 59).

It is now possible to consider the areas of skin of the face and neck which had possessed placodes corresponding to the cranial nerve ganglia. They comprise:

¶ An area related to the eye and fronto-nasal process and possibly more of the area supplied by the ophthalmic nerve—associated with the profundus part of the trigeminal ganglion.

¶ A maxillary-mandibular region possibly smaller than the above.

¶ The region of the external auditory meatus and below and behind the ear—associated with the VII cranial nerve and ganglion.

¶ A small area on the rostral edge of the triangular area of skin in front and lateral to the larynx and beneath the chin associated with the IX cranial nerve and ganglion.

¶ A triangular area of skin in front and lateral to the larynx associated with the X cranial nerve and ganglion.

If we examine again the patterns where sweating may be retained on the face after cervico-dorsal sympathectomy it will be seen that the above areas fit these patterns remarkably closely. The upper part of the central mask area of the face corresponds to that of the ophthalmic (profundus) area and will be continuous with that around the upper and lower lips (maxillo-mandibular). No sweating is to be observed over the point of the chin which would correspond with the site of the early fusion of the mandibular processes. Sweating is sometimes to be observed around the external auditory meatus and below and behind the ear corresponding to that of the VII cranial nerve. The area of sweating over and lateral to the larynx will correspond with that of the X cranial nerve (and possibly also the IX), as was realized by Frazer when he considered Head's diagram.

CONCLUSION

This hypothesis assumes that not only could there be retained nervous connections between these areas of skin and the appropriate cranial nerves, but also that autonomic efferent fibres can take this pathway. It would be most difficult to prove this by an examination of embryological material, but the association of these sweating patterns with the original sites and connections of the placodes may well be significant. It has already been shown that the connections to the area of skin over the larynx must be by nerves, since they can be blocked

by local anaesthesia. Such a pathway would pass above, i.e. rostral to, the hypoglossal nerve and might well be in the periarterial plexus of autonomic nerves around the branch of the occipital artery to the sterno-mastoid below which the hypoglossal nerve is hooked as it gives off its ramus descendens. In this and other areas of the face there are plenty of fine nerve fibres to be seen in the embryo, but it is impossible to say whether or not they are definitely connected with autonomic efferent ganglion cells. The proof is more likely to be made by observation after disease or injury, such as in those cases which were discussed in the previous section.

§3. GUSTATORY SWEATING

This phenomenon consists essentially of sweating on the face in response to eating. In normal people it is not ordinarily seen except in response to eating highly spiced or bitter foods, though cheese and chocolate may also be excitants in certain individuals. The particular interest of this phenomenon is that in normal individuals it is often maximal in the central part of the face and on the forehead—indeed, in much the same area as sweating is retained after cervico-dorsal sympathectomy.

Some babies, when fed tepid orange juice from a bottle, also sweat in this region.

Lee (1954) has shown recently that the area involved may vary in different individuals. Of particular interest is the fact that it may occur in localized areas, or on one side of the face only, and that in such cases, as has been reported by Guttmann (1931) and List and Peet (1938*d*), there may be complete or relative thermoregulatory anhidrosis on the affected side. Indeed, Haxton (1948*a*) has described a number of cases upon whom it was only noticed after 'cervico-thoracic ganglionectomy'. Unfortunately, he does not describe the exact distribution of this abnormal sweating in the cases he observed.

A localized variety of abnormal facial sweating was first described by Frey (1923) and named the auriculotemporal syndrome due to the occurrence of profuse sweating in the area of skin supplied by that nerve in the pre-auricular region. Such cases may be seen frequently after wounds in the maxilla or following suppurative parotitis. This syndrome was apparently known to Duphénix in 1757 and to Baillarger in 1853. Clinical accounts have been given by Thomas (1927), Kaminsky (1929) and Fridberg (1931). Rappoport is stated to have described a case of psychic induction of sweating—produced by the sight of a lemon being cut. Ford (1933) described four cases of the 'crocodile tear' syndrome, which was always consequent on facial palsy. This consists of associated lachrymation and sweating on eating. Russin (1939) described another

case, and accounted for the phenomenon by the suggestion of aberrant regenerating fibres of the facial nerve. Lachrymation did not occur with purely masticatory movements, but required the added stimulus of bitter, sour or tasty foods. Other accounts have been given by Boyer and Gardner (1949), who showed it could be prevented by intracranial section of the glossopharyngeal nerve, and Chorobski (1951), who suggested a theory of transaxonal stimulation of damaged axons. More carefully investigated accounts of the auriculotemporal syndrome have been given by Needles (1936), and List and Peet (1938*d*). Up to this time the most popular explanations had included that of the local diffusion of acetylcholine from nerve endings in the parotid gland which could act directly on the sweat glands, and that the activity of the parotid gland itself compresses the nerve fibres to the sweat glands. List and Peet, however, favoured the theory of local irritability of the cholinergic nerves to the sweat glands—possibly after regeneration. More completely investigated cases have been described by Langenskiold (1946), Haxton (1948*a*), Freedberg, Shaw and McManus (1948), who favour a theory of supersensitivity to acetylcholine or to histamine (Tankel, 1951) and Glaister, Hearnshaw, Heffron, Peck and Patey (1958) who believe the syndrome is due to aberrant fibres of cranial origin.

The localized area of sweating may not always be in the auriculotemporal region, and a particularly interesting case, in which it occurred in the submental region, is described by Uprus, Gaylor and Carmichael (1934) and another by Young (1956). Both cases had had glands of the neck excised through the right sternomastoid region in childhood. In the case recorded by Uprus *et al.* two years later, sweating was apparent in the submental region on this side, but was always preceded by flushing. Eating an apple was the best excitant. These workers demonstrated a distinct rise in temperature on the affected side when the patient was given an apple to eat, but this rise was not apparent on the opposite side. Heating the patient, however, produced a greater rise in temperature on the opposite side. In order to investigate the afferent pathway, they first showed that pieces of apple placed in either side of the mouth produced no response, but when the apple was chewed and swallowed, flushing and sweating resulted. Chewing wool, which was tasteless, produced no response. Similarly, the taste of salt, sugar, tartaric acid, quinine on the front of the tongue produced no response, but swallowing the acid or apple produced a momentary flush. Local anaesthesia with cocaine of half the tongue on the affected side did not prevent the response.

In investigating the efferent pathway they found that an intravenous injection of acetylcholine produced generalized flushing except in the abnormal area, whereas an injection of atropine, followed by eating an apple, produced flushing only in the abnormal area, but no sweating.

They then injected local anaesthetic into the region of the anterior cutaneous nerve of the neck and the great auricular nerve. This produced loss of sensation in the abnormal area, but on eating an apple again, flushing and sweating were evident as before. Following this, they injected the region of the lingual nerve distal to the site where the chorda tympani joined it. This caused loss of taste and touch in the anterior two-thirds of the tongue and suppression of saliva from the submandibular duct. Eating an apple after this injection caused no flushing or sweating in the abnormal area—this evidently had blocked the efferent pathway. These workers believed that the lingual nerve does not contain any efferent fibres other than those secretory or vasomotor fibres which come to it by virtue of its association with the chorda tympani. This cannot be correct, for Wilson (1934) showed that there must be other fibres joining the roots and branches of the trigeminal nerve. It appears, therefore, that in this case the afferent pathway was via the glossopharyngeal nerve (IX), and that the efferents were present in the lingual nerve though they did not necessarily come from the facial (VII) via the chorda tympani. They could have taken this route, but they could also have come from the glossopharyngeal via the tympanic plexus and thence to the chorda tympani or directly to the branches of the trigeminal distal to its ganglion as has been described by List and Peet (1938*d*)—see Fig. 59.

It is more likely, however, that the local injection of the lingual nerve also involved the inferior dental nerve at the mandibular foramen, and therefore that the mental nerve was also involved in the anaesthetic block. Certainly the effector pathway was not via the anterior cutaneous nerve of the neck, which is the normal sensory supply to this region.

Young's case (1956) was very similar to the above, and after the administration of belladonna also showed the continuance of the erythema in the affected area, but no sweating. In this respect these findings are rather similar to the original observation of Heidenhain (1872) that stimulation of the chorda tympani produced a vasodilator effect in the submandibular gland, and in the tongue (1883), which was not abolished by atropine sufficient to prevent salivary secretion. Hilton and Lewis (1956 and 1957) now believe that this vasodilatation was due to the action of bradykinin, a polypeptide formed by an enzyme produced by the cells of the salivary gland, and which can pass through the duct wall. Atropine does not prevent the production of the enzyme. This bradykinin-forming enzyme is also present in human forearm sweat, and the bradykinin content of subcutaneous tissue increases when the subject is heated. It has been concluded by Fox and Hilton (1957 and 1958) that this mechanism contributes to the vasodilatation which develops in the skin at the same time. Such a mechanism is

most probably involved in the localized areas in Uprus *et al.* and Young's cases and the cases of gustatory sweating in other areas of the face.

It is significant that Young found that local anaesthetic block in the region of the stellate ganglion on the affected side produced a Horner's syndrome but did not prevent the gustatory sweating. Similar findings have been observed in a case of auriculotemporal syndrome by Freedberg *et al.* (1948—*Case 2*) in which sweating was not abolished after injection of local anaesthetic into the superior cervical ganglion.

Tarlov and Herz (1947) have also described an unusual case in which unilateral emotional sweating was confined to the supraorbital area. Section of this nerve completely relieved the sweating in the area of resulting analgesia, except that some sweating persisted over the mid-line in the glabellar region.

Coldwater (1954) has recently treated two cases of auriculotemporal syndrome by resection of the auriculotemporal nerve and the superficial temporal artery and vein, together with the anastomotic branches which the facial nerve makes with the auriculotemporal nerve. Prior investigation of one case had shown that local anaesthetic block in this region would prevent the gustatory sweating, but that local anaesthesia of the cervical sympathetic trunk, lingual and chorda tympani nerves and the submandibular ganglion were all unavailing. Coldwater postulated that the efferent pathway of the syndrome was from the facial and thence via its anastomotic branches to the auriculotemporal, lachrymal and zygomaticotemporal. He stated that he did not dare confine his section to these anastomotic branches. Gardner and McCubbin (1956) have shown that in one case intracranial section of the glossopharyngeal nerve abolished the syndrome, but in another case this was only partially successful. *Evidently the facial or glossopharyngeal nerves, or both, can* provide the autonomic efferent pathway in these cases.

Wilson (1934) noted that after superior cervical ganglionectomy, pilocarpine would still cause sweating on the face. He reconsidered the account of Billigheimer (1921) and Woolard and Norrish (1933) that pilocarpine acted on some fibres in the spinal nerves other than the secretory sympathetic fibres. He also recollected that Cushing (1931) had suggested that pilocarpine acted upon a parasympathetic centre in the hypothalamus when the drug was injected intra-ventricularly. Wilson eventually concluded that it acted directly on the sweat glands and had only a peripheral action. *He therefore thought it unlikely that* the sweat glands had a double innervation.

In 1936, however, Wilson retracted his earlier opinion. He now *suggested* that the sudomotor nerves to the face were of two types—the sympathetic secretory fibres from the superior cervical ganglion and an accessory set. *The sympathetic branches were supposed to leave the* carotid plexus and join peripheral branches of the trigeminal probably

extra-cranially, and were not distributed with the peri-arterial nerves. He thought the accessory set probably arose from the brain stem directly and joined the trigeminal at some point distal to the sensory root, and were also distributed with the trigeminal branches. This supposition is very similar to that originally propounded by Guttmann and List (1928). Wilson thought the latter set were normally distributed to the sweat glands of the face, and his diagrams show a typical 'mask' area extending well up onto the forehead. There was no evidence that they were important under physiological conditions, though they became more evident after sympathectomy. They were cholinergic in type. In his experiments he found that procaine nerve block of the supraorbital always prevented gustatory and thermal sweating in this area. One case which he described is particularly interesting. The patient had been treated with radium (for an angioma of the tongue) which produced a neuritis of the lingual and glossopharyngeal nerves on the right side. Section of the sensory root of the trigeminal was performed four years later, and subsequently a section, but *extra-cranial*, of a portion of the glossopharyngeal. This was followed by a right superior cervical ganglionectomy, and ten days later the patient noticed gustatory sweating over the right side of the face. At this time there was complete anaesthesia in the distribution of the trigeminal of the right side, but signs of regeneration of the glossopharyngeal. Thermoregulatory sweating was present on the left side of the face but absent on the right.

Haxton (1948*a*) reported four cases in which gustatory sweating made its appearance out of twelve cases he examined after 'cervico-thoracic' ganglionectomy. In these cases the stellate ganglion had remained intact and no Horner's syndrome had been produced. A similar case had been described by Lewis (1938). Haxton found that if the gustatory sweating was unilateral, thermoregulatory sweating was diminished on the affected side—but this was not so in Lewis's case. The gustatory sweating was often preceded by flushing, but if unilateral, only the opposite side blushed when the patient was embarrassed. Haxton also described one case of birth injury due to forceps, with a scar in the pre-auricular region. Sweating and flushing on eating fruit had been apparent in this region since childhood. Section of the cervical sympathetic chain just above the middle cervical ganglion produced a Horner's syndrome but did not relieve the condition. Subsequent thermoregulatory sweating was equal on the two sides.

In all his cases, Haxton reported that a procaine block of the stellate ganglion region in the upper thorax prevented further gustatory sweating—though this could not have been a precise injection, since the opposite side was sometimes also involved in the block! If sufficient local anaesthetic were injected beneath the prevertebral fascia on one side and was able to infiltrate across mid-line to affect the opposite

sympathetic chain, it is obvious that it could have extended upwards or downwards beneath the prevertebral fascia even more readily. The *exact site at which the fibres concerned in the gustatory reflex were* blocked must still remain a matter of conjecture. Horner's syndrome and other evidence of sympathetic paralysis on the injected side was, of course, produced by the local anaesthetic.

Tankel (1951) describes a single case of gustatory sweating that opens up a new line of speculation. In this case sweating on eating was present on one side of the face only, and was not preceded by flushing. Sweating was apparent on the forehead, over the eye, side of nose, and cheek and upper lip and chin, and over the parietal region. There was no Horner's syndrome, the pupils were equal and no abnormality detected in the central nervous system. Investigation of the afferent pathway showed that this was either via the chorda tympani branch of the facial (VII) or by the glossopharyngeal (IX). Tasteless cotton-wool did not provoke sweating. Cocainization of the tongue did not prevent the gustatory sweating, since apparently not all the taste fibres to the glossopharyngeal could be anaesthetized by this method.

Tankel performed a series of tests to determine the effector pathway. Procaine block of the supraorbital nerve produced complete anhidrosis in the anaesthetic area. Similarly an injection of 20 ml. of procaine solution in the region of the stellate ganglion at the base of the neck caused gustatory anhidrosis and a rise in the skin temperature on that side of the face. As with Haxton's cases, however, an injection of so large a volume of fluid does not localize the site of the gustatory sweating pathway with precision. Injections of acetylcholine and of pilocarpine both produced more sweating on the affected side, and atropine prevented gustatory sweating. After the injection of tetraethylammonium bromide spontaneous sweating ceased all over the body and generalized flushing became apparent; but gustatory sweating was not inhibited. On heating the patient, more sweating was apparent on the affected side of the face—as had been noted by Wilson (1936) in a case of syringomyelia, and by Lewis (1938) in a case after sympathectomy. Tankel then tried the effect of a subcutaneous injection of histamine: he found that sweating was produced only on the affected side and that no generalized sweating was produced—this absence of sweating is the usual result unless an overdose of histamine produces central side effects. Following up this unexpected finding, he then tried the effect of the antihistamine drugs. These he found inhibited the gustatory sweating in proportion to their antihistaminic activity. On combining the effects of heating with those of antihistaminic drugs, sweating appeared most on the unaffected side. This indicated that the drugs did not inhibit ordinary thermoregulatory sweating, but only the gustatory sweating and some of the thermoregulatory sweating on the affected

side of the face. He concluded that the sweating on the affected side of the face was mostly due to histamine activity.

This interesting report introduces a new line of investigation, but does not yet appear to have been followed further by other workers. The finding that tetraethylammonium bromide, which usually blocks the preganglionic-postganglionic autonomic synapses by depolarization, was not effective in this case of gustatory sweating would appear to favour the idea of special nerves supplying the sweat glands in gustatory sweating which had no synapse in their pathway and are therefore similar to those portrayed by Guttmann and List (1928). The fact that histamine appears to be concerned in the production of the gustatory sweating reflex suggested a complicated explanation to Tankel and to Wilson, with whom he had consulted. Obviously the effects of histamine and antihistamine drugs would have to be studied on other suitable cases.

Lee (1954) has made a careful study of the occurrence of gustatory sweating in the tropics. He found that if chillies were used as an excitant, gustatory sweating is easily elicited in normal subjects in the tropics. It was always symmetrical, but there was much individual variation—from his illustrations it appears to be most frequent on the forehead and central part of the face. When elicited by the above excitants, it was invariably accompanied by flushing of the face, salivation, lachrymation and nasal secretion, though the intensity of each varied individually (*n.b.* the latter three are due to parasympathetic activity, also that flushing was not apparent in Tankel's case). Lee found that sweat gland activity in response to a gustatory stimulus exhibited features of reflex action—recruitment, facilitation and adaption or fatigue. He found that other substances such as sugar or vinegar were not so effective as chillies and that mechanical or thermal stimuli were ineffective. The sensitivity was greatest on the anterior part of the tongue. This is rather different from the usual findings by other observers and may be due to the fact that all Lee's subjects were young men. Possibly in older cases the taste buds in the anterior two-thirds of the tongue have atrophied as has been reported by Brodal (1948—*page 232*).

Lee confirmed that the secretory gustatory sudomotor fibres are cholinergic, but otherwise made no attempt to investigate the effector pathway although he was aware of Tankel's paper. Lee believed that gustatory sweating was most evident on the same areas of the face as those in which it was evident on thermoregulatory sweating, and it was better seen in these areas when the body was warm. This, of course, is in contradistinction to cases reported earlier in which it has developed after sympathectomy.

PERSONAL OBSERVATIONS

The author has observed two cases who showed localized abnormal sweating on the face.

RIGHT GUSTATORY SWEATING (FIG. 62*a–h*)

CASE H.F. This patient, a woman of forty-six, had had a painful lump excised from the right side of the neck in childhood. For the past four years she had begun to sweat violently on the right side of the head, face and neck. This was precipitated by eating meals and especially by cheese, but not by the sight or smell of food. No abnormality was detected in the central nervous system. Fig. 62*a* shows the pattern of sweating in response to eating cheese. There was occasional slight flushing on the right cheek. The sweating has been made evident by the application of quinizarin powder. It will be observed that sweating is principally on the right forehead and above the eyebrow, on the right side of the nose and the cheek near by, and on the upper and lower lips. A better full-face view may be seen in Fig. 62*e*. On thermoregulatory testing it will be evident that sweating is greater on the affected side and is very profuse on both sides of the forehead (Figs. 62*b*, *c*, *d*). It is also considerable in the skin of the front of the neck where slight gustatory sweating was also evident.

Attempts were made to block the sudomotor reflex pathway by local anaesthetic. On two occasions injections of procaine were made into the region of the stellate and first thoracic ganglia by a posterior approach. This proved to be very difficult to carry out at this level, but minimal sympathetic paralysis was produced with evidence of a slight Horner's syndrome. Fig. 62*e* shows that the gustatory sweating produced by eating cheese was not abolished, although slight myosis and slight ptosis has been produced on the right side. On a third occasion procaine was injected in the region of the lower end of the cervical sympathetic chain at the base of the neck by an anterior approach. This readily produced a paralysis of the cervical sympathetic with a marked Horner's syndrome. Subsequent eating of cheese produced slight sweat gland activity around the left upper lip and also around the left eyebrow, left side of nose and left chin, but on the right side there still remained five functional sweat glands on the upper lip. These may be seen in the photograph, Fig. 62*f*. This photograph may occasion some surprise in that the Horner's syndrome is no longer apparent. It was taken by electronic flash in the dark, and under such conditions, as has been reported earlier by Mutch (1936), the pupil of Horner's syndrome will dilate in the dark to the same diameter as that of the normal side. It should be noted that the right pupil is still slightly smaller. It is also evident that the upper eyelid has retracted and that ptosis is no longer present. On subsequent thermoregulatory testing, it is evident (Fig. 62*g*) that sweating is now greater on the left side though it is apparent on the right side also, due to the anaesthetic block wearing off before the test was complete.



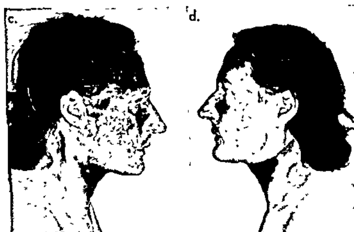


Fig. 62. Gustatory sweating. Case H.F.

a. After eating cheese

b. After general body heating

c. Affected side, after general body heating

d. Normal side, after general body heating





e. After eating cheese.
Attempted right cervical sympathetic block

N.B. Partial Horner's syndrome on right.

f. After eating cheese.
Repeated procaine block —almost no sweating

N.B. Horner's syndrome not evident in dark.

g. After heating. Right procaine block passing off

h. Sweating pattern three weeks after right stellate and part middle cervical ganglionectomy

N.B. Horner's syndrome on right.



From these observations it was concluded that the patient had an outflow of the pupilodilator fibres from a rather higher level than usual—probably C.7 or C.8. It was also conjectured that the greater amount of the effector pathway concerned with the gustatory sweating was conveyed in fibres running with the sympathetic chain at about this level, though apparently not all such fibres were blocked by the local anaesthetic.

Subsequent right stellate ganglionectomy was performed with resection also of the lower part of the middle cervical ganglion. Eight weeks after operation, thermoregulatory testing was carried out and showed the pattern to be seen in Fig. 62*h* (and also in Fig. 21, Case H.F.). It is evident that sweating activity has been retained in the central mask of the face, as is usual, though surprisingly, in view of the considerable gustatory sweating on the forehead originally, the latter now appears to be anhidrotic. The persistence of sweating in the greater part of the arm has been discussed earlier. On questioning, the patient denied that she had any further sweating on the right side of the face on eating but, on close observation, a slight degree of gustatory sweating was present on the right upper lip and in the centre part of the left side of the face.

LEFT FACIAL HYPERHIDROSIS—EMOTIONAL

CASE B.B. This patient, a man of forty-six, had shown profuse sweating over the left forehead for four years, which was associated with headaches in the left supraorbital region. The sweating was not induced by eating but seemed to be emotional in origin and was worse in winter than in summer. There was no history of injury. Horner's syndrome was not apparent, but the pupil on the left side was slightly larger and there was a suggestion of lid retraction on this side. Otherwise, no abnormality was detected in the central nervous system, but X-ray of the cervical spine showed osteoarthritic changes in the cervical vertebrae with narrowing of the intervertebral joint spaces between 5th and 6th, and 6th and 7th cervical vertebrae.

Sweating was maximal in the ophthalmic and maxillary divisions on the left side of the face, and approximately equal in the mandibular divisions on either side. Electrical skin resistance measurements were made on this patient before operation and are illustrated in Fig. 63.

The figures marked on the diagram of the face show the relative conductivity of the different areas of skin. One unit represents the passage of two microamperes of current from a 4·5-volt battery. The symbol 10, therefore, can be calculated to indicate a resistance of the skin equivalent to 250,000 ohms. The larger numbers on the chart indicate a proportionately less resistance. It will be apparent that the areas of lowest electrical skin resistance are on the left supraorbital

region (up to 100 units), on the left pre-auricular and auriculo-temporal region, on the left side of the nose; and on the upper and lower lips, where they are equal on each side.

Observations on the hand blood flow both before and after operation were made by Professor Henry Barcroft of St Thomas's Hospital (Barcroft and Walker, 1949—*figure 5*). Vasomotor tone was greater in the vessels of the left hand than those of the right.

The left stellate and 2nd thoracic ganglia were resected at operation by an anterior approach. This produced an immediate Horner's syndrome on the left side and apparent anhidrosis of the left arm and left side of head, face and neck. Five days later, however, sweating was

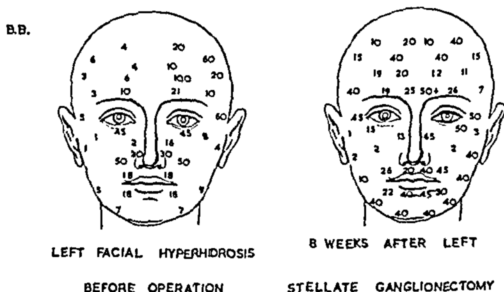


FIG. 63. Case B.B. Left facial hyperhidrosis. To show pattern of electrical skin resistance. Numbers indicate proportional values of current; high numbers indicate low resistance, low numbers indicate high resistance.

again apparent in the same areas where it had been maximal before operation, except in the lower part of the left face which was still relatively anhidrotic.

Measurements of the skin resistance were made on various occasions and the readings obtained eight weeks after operation are shown in Fig. 63. It will be observed that over the lower part of the face the numbers are relatively symmetrical, as had been observed before operation, except that now the resistance was slightly lower on the left cheek as compared with the right. The left supraorbital region, however, and infraorbital and left side of the nose, still show a much lower electrical resistance (higher conductivity) as compared with the right side. Indeed, the only significant change in the skin resistance, before and after operation, is that it has been increased in the left pre-auricular and auriculo-temporal areas following on the sympathectomy. The central mask of the face area remains relatively unaffected by the sympathec-

tomy. Blood-flow measurements in the hands (performed by Professor Barcroft) indicated that a small degree of vasomotor control had been retained on the left side.

These two cases indicate that resection of the cervical sympathetic chain in the region of the stellate ganglion does not necessarily interrupt the abnormal gustatory or emotional sweating pathways to the central part of the face. Sweat glands in the upper part of the forehead, the auriculo-temporal area and pre-auricular areas, however, if they are concerned with abnormal sweating, are supplied by pathways which may be severed by stellate ganglionectomy.

SUMMARY

From the clinical cases reported in the literature and from the author's own observations, the following summary may be made of the principal characteristics of abnormally evident gustatory sweating.

¶ Acid, bitter or spicy foods (sometimes chocolate) initiate a reflex in which the sensory arc is conveyed by taste fibres in the glossopharyngeal or facial (chorda tympani) nerve.

¶ An almost immediate local flushing on the face which may not always be apparent (e.g. Case H.F.), or present (e.g. Tankel's case and Case B.B.).

¶ A few seconds' delay, then sweating in a local area—or, if generalized, then mostly in the central mask area of the face with variable extensions onto the forehead. Usually sweating is in the same area as the flushing, but they are not necessarily identically distributed.

¶ Pain sometimes precedes sweating.

¶ Other autonomic activity may often be diminished in the area—i.e. general heating of the body usually produces less sweating on the affected side (or less vasodilatation—Uprus *et al.*).

¶ When sweating occurs in localized areas there may be evidence of peripheral nerve injury, as in the auriculotemporal syndrome and in the submental sweating syndrome.

¶ Cases may first show abnormal gustatory sweating after cervicodorsal sympathectomy for some other condition. In these cases thermoregulatory sweating is usually reduced or absent.

¶ In certain cases, particularly those due to injury of peripheral nerve or whose aetiology is unknown, the local injection of anaesthetic solution in the region of the stellate ganglion (or even superior cervical ganglion—*Case 2* of Freedberg *et al.*) may not interfere with the gustatory sweating, but if the volume of anaesthetic solution injected is large, then part or all the gustatory sweating may be abolished.

DISCUSSION AND CONCLUSIONS

The associated vasodilatation, which may often precede the appearance of sweating, has been explained by Hilton and Lewis (1956 and

1957) on the basis that cholinergic nerves to salivary or sweat glands, besides activating a secretion from the gland, also cause the gland to produce an enzyme which acts on globulins in the blood to produce bradykinin. The latter is a powerful vasodilator, and thus vasodilatation is a secondary, rather than a primary, action of these nerves. Such mechanism is probably the one involved in the bucco-labial flushing originally observed in the rabbit by Jolyet (1878) and in the dog by Dastre and Morat (1880 and 1884) whose original experiment appears to have been very similar to that of Murray and Thompson (1957*b*—*page 217*). In this respect it is interesting to recall that Barcroft (1907) and Gaskell (1916—*page 93*) thought that the flushing was explainable by the action of metabolites due to such secretion rather than as a result of stimulation of vasodilator nerves, such as those in the cervical sympathetic suggested by Dastre and Morat. Emmelin (1955) has administered sympathicolytic drugs, and observed changes in blood flow and salivary secretion, in the submaxillary gland of the cat, which fit in well with Barcroft's original observations. Other aspects of vasodilator nerves have been reviewed by Burn (1938), Uvnäs (1954) and Folkow (1955), but it would seem that many of their conclusions should now be reconsidered.

Hilton and Lewis suggest that since injection of acetylcholine has no vasodilator or secretomotor effects after atropine, secretomotor nerve fibres in the chorda tympani are in some way resistant to the action of atropine. Either they release some other transmitter substance in addition to acetylcholine, or the latter is released in such close proximity to the receptor structures that atropine cannot completely block its access to them. In view of Tankel's observations of histamine on gustatory sweating it is possible that some similar H-substance may also be produced on stimulation of cranial autonomic nerve fibres. Hilton and Lewis actually stimulated the chordo-lingual nerve and not just the chorda tympani. It is possible that other fibres—e.g. sensory—might have been stimulated in the mixed nerve.

Blushing due to embarrassment is also said to be abolished after cervico-dorsal sympathectomy by Lewis and Landis (1930—*page 166*). and it has been suggested that it should be regarded as being produced by inhibition of sympathetic vasoconstrictor impulses. Lewis and Landis, however, were not entirely satisfied that this explanation was sufficient to account for all flushing on the face from other causes. Anonymous recent opinion (*Brit. med. J. 1957*, i, *page 416*) suggests that blushing is a parasympathetic function.

Chorobski and Penfield (1932) and Penfield (1932) have shown that in monkeys cerebral vasodilator fibres are present in the facial nerve and leave it by the greater superficial petrosal nerve to synapse with ganglion cells in the region of the cavernous sinus. These ganglia have

also been verified in the rabbit by Gellert (1951). Hertzman and Dillon (1939*a* and *b*) have shown experimentally by photoelectric plethysmography in man that simultaneous waves of vasomotor activity caused vasoconstriction in the extremities and vasodilatation in the skin of the forehead, but in the nasal septum the responses were variable. They concluded that there must be selective vasomotor patterns in the skin and the nasal septum.

Schumacher, Ray and Wolff (1940) and Schumacher and Wolff (1941) have confirmed in man the proposition of cerebral vasodilator fibres and Gardner, Stowell and Dutlinger (1947) report that resection of the greater superficial petrosal nerve was effective in the treatment of unilateral headache and that lachrymation and nasal congestion were also relieved on the operated side. Blier (1930) had suggested that there might be some vasodilator fibres for the nasal cavity in the sympathetic system which probably had their ganglion cell stations in the superior cervical ganglion, and that these were in addition to those from the sphenopalatine ganglion. The experimental evidence, however, for Blier's hypothesis appears to be rather weak. Higbee (1949) concluded that vasoconstriction of the nasal mucosa was the dominant effect of stimulation of sympathetic nerve fibres, whereas parasympathetic fibres from the sphenopalatine ganglion were vasodilator in action.

The fibre content of the facial nerve is of interest. Foley and DuBois (1943) showed that 15 per cent of the total axons in the facial nerve were autonomic efferents and of these, 70 per cent. left via the greater superficial petrosal and 30 per cent. via the chorda tympani. Their findings were confirmed approximately by van Buskirk (1945), who in a comparative study on the facial nerve found that autonomic efferents comprised 7 per cent. of the total in the dog, 2 per cent. in the cat and as much as 24 per cent. in man. He did not find any efferents in the auricular branch of the vagus which, according to him, is made up entirely of sensory fibres, and he thus confirms the conclusions of Bruesch (1944).

There seems to have been little work performed on the proportion and function of the autonomic efferents in the glossopharyngeal nerve since the time of Loeb (1869). Cobb and Finesinger (1932) showed that stimulation of the vagus nerve produced a reflex vasodilatation of the cerebral vessels and that the efferent pathway was mediated by the facial. Their findings have confirmed the earlier report of Forbes and Wolff (1928). Foley and DuBois, severally and jointly, have performed many histological counts on the fibres in the IX, X, and XI cranial nerves (1933, 1934, 1936, 1937 and 1945). These were all performed on the cat and provide little information in regard to the autonomic efferents, except that the anatomy of the tympanic branches of the glossopharyngeal and of the vagus is apparently different in that animal from that in man.

Some support, however, for the possibility of sudomotor autonomic efferents in the glossopharyngeal nerve is provided by Rexed (1944—Table VII). In this table, showing the calibre spectra of the cranial nerves in a human new-born child, it will be evident that there is a peak of finely myelinated fibres, one to two microns, present in the IX cranial nerve. Many of these may, of course, be sensory—as presumably they all are in the trigeminal (V). It is odd to note that at this age such a small proportion of finely myelinated fibres are present in the facial (VII). Possibly, however, some of the fibres of what should have been the nervus intermedius had been included in the vestibular portion of the auditory (VIII) nerve. This has often been found to be the case in man by van Buskirk (1945).

Larsell (1918, 1950) has traced the fibres of the nervus terminalis into the olfactory epithelium in mice and other mammals. Axons of multipolar neurones are located in the nasal septum, and are distributed to Bowman's glands and apparently to blood vessels in the olfactory mucosa and vessels related to the olfactory bulb. He believes that the preganglionic fibres probably arise in the supraoptic regions. The nervus terminalis has been described in man (Pearson, 1941) as providing filaments to the cerebral blood vessels in the anterior cranial fossa, but filaments from it to the peripheral vessels have not yet been recognized in man. Although it is possible that this 13th cranial nerve may provide an autonomic efferent pathway to the nasal mucosa, its fibres are few in number and it is improbable that they would be sufficient to provide the pathway to the area of retained sweating in the central mask of the face. They are mentioned here in order to discount the possibility that these are the relevant pathways for the sudomotor fibres.

Other aspects of autonomic efferents to the face from the cranial nerves have been discussed more fully by the author elsewhere (Monro 1954*b*—*pages 189–227*).

The idea of the face receiving an autonomic efferent supply to the skin from one or more of the cranial nerves may be more acceptable if the skin around the proctodaeum is considered as well as that of the stomatodaeum. Besides the invariable finding of retained sweating in the central mask of the face after stellate ganglionectomy, it has been shown earlier that the skin of the perineum also retains a low electrical resistance after lumbar sympathectomy. These observations have also been made by Ray and Console (1948), who showed that sweating was retained in the central part of the face in one case of 'total sympathectomy'. The area involved in retained sweating in the perineum corresponds closely to that of the 4th sacral dermatome. Although this has never been precisely delineated in man, the suggestion for it made by Head (1893) corresponds very closely with that observed in the macaque by Sherrington (1893) (9th post-costal dermatome).

Häggqvist (1937) made a fibre analysis of the anterior roots of the macaque and had shown a second outflow of finely myelinated fibres in the lower sacral and coccygeal region. In man, Swensson (1938) and Rexed (1944) have shown that this outflow of fine myelinated fibres is most frequent at the 4th sacral nerve root—closely corresponding to the dermatome in man where retained sweating is observed.

Thus two areas of the body show retained sweating after the appropriate sympathectomy. Both, and only these areas, have parasympathetic nerves which are known to supply structures in this region. Do these parasympathetic nerves supply the sweat glands also, or is there an outflow of so-called sympathetic but similarly cholinergic nerve fibres which is concealed or closely approximated to the parasympathetic outflow? (See p. 184.)

The difficulty is the proof. If it were possible to combine a lesion of the stellate ganglion with a lesion of such an appropriate autonomic cranial nerve, then complete anhidrosis should be produced on that side of the face. No such case has been observed. A case of bilateral intra-petrous facial palsy showed diminished facial sweating on both sides, but nowhere was it completely absent—presumably the glands were supplied from the sympathetic cervical chain. Unilateral paralysis of the facial and auditory nerves due to 'acoustic neuroma', which had been excised, and with partial involvement of the V and IX cranial nerves, similarly showed no absolute anhidrosis of the face. A case on whom the sensory root of the trigeminal nerve had been sectioned, and upon whom a stellate ganglionectomy had also been performed, showed some recovery of function from the sympathectomy, but nowhere complete anhidrosis. From the literature we find:

(1) Section or block of peripheral branches of the trigeminal produces complete anhidrosis in the analgesic area (List and Peet 1938*d*) and others.

(2) Malignant parotid tumour involving the bone of the middle cranial fossa produces *absolute* anhidrosis of the lips, cheek, side of nose and lower eyelid (List and Peet). It is therefore evident that it must be possible to block both sets of nerves simultaneously. This junction must be distal to the trigeminal ganglion, for otherwise central sweating on the face remains. Section of the sensory root of the trigeminal, followed by superior cervical ganglionectomy, showed sweating on this side of the face ten days later (Wilson 1936). This case (*Case 3*) also had a recent section of the glossopharyngeal nerve, but this section was extracranial and therefore the tympanic branch presumably remained intact.

The cases of gustatory sweating in the submental region (Uprus *et al.*, 1934, and Young, 1956) did not necessarily receive their efferent fibres from the chorda tympani branch of the facial, since the sudomotor fibres may have already been present in the lingual nerve before the chorda tympani joined it. The author can find *no case in the litera-*

ture, or his experience, which shows a lesion of the cervical sympathetic and of the intracranial portions of the facial or glossopharyngeal nerves. Were such a case to be found, it might show complete anhidrosis of the central part of the face.

There is thus no reason for believing that either the facial or the glossopharyngeal (or both) may not provide another sudomotor pathway to the central part of the face. The afferent pathway for gustatory sweating is via the facial (VII), or probably more commonly the glossopharyngeal (IX). The efferents could be via the greater superficial petrosal branch of the facial or the communication of the facial with the lesser superficial petrosal, or even the branches of the lesser superficial petrosal from the tympanic plexus which comes originally from the tympanic branch of the glossopharyngeal (Fig. 59). The efferents may synapse with ganglion cells around the internal carotid artery in the region of the foramen lacerum (Chorobski and Penfield, 1932), in the infratemporal region, as illustrated by Reichert and Poth (1933—*page 135*) and by Chorobski (1951—*page 310*), or along the chorda tympani and lingual nerves as have been described by Langley (1890) and Snell (1958).

Facial hyperhidrosis, or the localized variety—auriculotemporal syndrome—have some features in common with 'perilesionary hyperhidrosis' as described by Guttmann (1940*a*). In this, abnormally increased sweating developed around an anhidrotic area after a few days and may even be evident without heating the patient. Later this spontaneous sweating disappears, but may still be recognized by its rapid onset on general heating of the body. This is evident in the author's and Tankel's cases.

It has been evident that inferior cervical ganglionectomy, or procaine anaesthetic block in this region, will greatly reduce sweating all over the face, and may appear to abolish gustatory sweating. In the two cases of gustatory sweating observed by the author, however, complete gustatory anhidrosis was not produced by either procedure, and a few sweat glands on the upper lip could still produce sweat on gustatory stimulation, even though a large volume of procaine had been injected at the level of the 8th cervical vertebra and had produced a Horner's syndrome. It is possible that the preganglionic fibres which produce this sweating may have left the vertebral canal at a higher level than is usual for the upper level of the thoraco-lumbar outflow of the sympathetic.

Van Buskirk (1941) has described the presence of apparently autonomic fibres in the cervical vertebral canal. These were found in the sinuvertebral nerve (Luschka), which lies on the lateral region of the floor of the canal and sends fibres to vessels over the dura mater and to the vertebrae. Van Buskirk performed anatomical experiments on cats

and made dissections on human foetuses. He concluded that this nerve offered a pathway for sympathetic fibres to the upper cervical nerves which would by-pass those running through the inferior cervical ganglion and the cervical sympathetic chain in the neck. The number of such fibres, however, is relatively small, and most were unmyelinated and appeared to be distributed to blood vessels. Van Buskirk's findings have been confirmed in cats by Christenson and Polley (1950). It seems unlikely that this pathway is important in normal sympathetic activity in the head and neck, but possibly, after the resection of portions of the cervical sympathetic chain, its importance may be increased.

Sheehan (1941) has shown that fine myelinated fibres are present in the anterior roots of all the cervical nerves, although they never number more than 100. Swensson (1938) and Rexed (1944) show a similar outflow of these fine fibres, though they do not state their numbers precisely.

Skoog (1947), in careful dissections of the cervical region in adults, has shown that intermediate sympathetic ganglia are to be found in relation to almost all the cervical nerve roots, and especially frequently in relation to the 2nd cervical (Fig. 73). Mitchell (1953) has recently suggested (*pages 32–33*) that these fine myelinated fibres and the intermediate sympathetic ganglia in relation to the upper cervical nerve roots might form alternative sympathetic pathways to the head and neck. Mitchell does not provide any experimental evidence in favour of this hypothesis, and the author has shown, in the chapters dealing with the lumbar intermediate sympathetic ganglia, that such pathways do not exist for the intermediate ganglia in relation to the 4th and 5th lumbar nerve roots. This does not exclude the possibility of such pathways in the cervical region. If such is the case they will provide another autonomic pathway to the head and neck which would fail to be interrupted by resection of a portion of the cervical sympathetic chain and stellate ganglion.

It should also be realized that other pathways alternative to the cervical sympathetic chain in the neck are present along the course of the carotid arteries and particularly the vertebral artery. Such possibilities are well seen in the illustrations to Skoog's article (Fig. 73). All these three possibilities must be remembered in considering the possible route of the pathway of sudomotor fibres to the central part of the face, which retains its sweating after stellate ganglionectomy. All these pathways might be partially or almost completely blocked by a large injection of local anaesthetic behind the prevertebral fascia at the base of the neck.

It appears that the missing link in this chain of possible autonomic pathways has now been supplied by Murray and Thompson (1956 and 1957*a* and *b*). They observed in the cat that after complete preganglionic denervation of the superior cervical ganglion, sprouts from the vagal efferent fibres in the adjacent nodose ganglion partly re-

innervated the superior cervical ganglion by way of existing communications. As a result, nictitating membrane contractions on the operated side could be produced by vascular and gastric reflexes, passing up the contralateral vagus. They suggested that this phenomenon might well be responsible for gustatory sweating, and this suggestion has received support elsewhere (*Brit. med. J. 1957*, i, *page 718*). The earlier experiments of Kirgis and Reed (1955) would appear to support these findings, and also the reports of Kuntz, Hoffman and Napolitano (1956) that in the cat fibres of the vagus normally contribute to the internal carotid nerve of the cervical sympathetic. Kuntz *et al.* thought that these fibres were probably afferent, since they were over 3·5 microns in diameter, but they do not exclude the possibility of an efferent contribution. They agree that complete sympathetic denervation of the head cannot be achieved by cervico-dorsal sympathectomy.

It is evident that if such a pathway, as Murray and Thompson suggest, can develop from the preganglionic fibres of the vagus, as a result of injury to the preganglionic fibres ordinarily supplying the superior cervical ganglion, they could also grow from the glossopharyngeal which is not far distant, especially in the infratemporal region, or from the facial nerve to the ganglion cells in the petrous region. Indeed, it is very possible that during normal development such connections of 'parasympathetic' preganglionic fibres may form synapses with 'sympathetic' ganglion cells of cholinergic type in the head region. It is apparent that Langley's (1905—*page 403*) original division into sympathetic and *para*-sympathetic outflows no longer holds for cholinergic nerves to sweat glands, although when he first used the term 'parasympathetic' he applied it only to the cranial and sacral systems seemingly as an abbreviation. Murray and Thompson (1957*a* and *b*) suggest that these new connections may also apply to ganglion cells whose axons have endings of adrenergic type—at least, those to the nictitating membrane. Presumably in the facial region they do not usually establish synapses with nor-adrenergic vasoconstrictor fibres unless the released bradykinin overpowers the vasoconstriction that would ordinarily be produced by stimulation of such a nor-adrenergic postganglionic neurone.

Some recent support for the suggestion that preganglionic fibres from cranial autonomic efferents can form synapses with adrenergic ganglion cells supplying the erector pili muscles in man has been provided by Herxheimer (1958). He has described a case in which gustatory sweating appeared on the neck and shoulder following a thoracoplasty on that side. On eating certain sweets or cheese, gooseskin appeared in the same area, but after heating the patient, sweating was much less on the face, neck, shoulder and arm on the affected side.

Plethysmography suggested absence of vasoconstrictor control in the hand and fingers. Herxheimer concluded that sprouts from the vagus had made connections with the sympathetic ganglion cells whose normal preganglionic fibres had been divided.

The evidence of this report would seem to confirm in man what Murray and Thompson had observed in the cat. It now seems almost certain that a similar process must account for gustatory sweating. Herxheimer did not consider the implications of the terminology of the preganglionic fibres involved, but obviously the prefix 'para' should no longer apply to 'sympathetic' autonomic pathways of this type.

In Dastre and Morat's original experiment (1880) on the dog they stimulated the central end of the cut vagus after previous avulsion of the superior cervical ganglion on that side. Vasodilatation was observed on the contralateral bucco-labial region—presumably as a result of an efferent discharge of the normal vagus via sprouts to the cells of the intact superior cervical ganglion on this side. Section of the intact vago-sympathetic trunk abolished the response.

In the central region of the face it would seem possible, on developmental grounds, that the cranial autonomic efferent preganglionic fibres establish connection with some of the ganglion cells supplying sweat glands to the region. The various other phenomena relating to gustatory sweating lend support to this hypothesis.

Although procaine anaesthetic block at the base of the neck appears to interrupt the greater part of gustatory sweating, it is unlikely to have extended so high as to involve the cranial nerves at the base of the skull. Although, therefore, it might appear that the facial and glossopharyngeal nerves could not be concerned in the efferent pathway of gustatory sweating, it has not been shown that the nerves, which are concerned with the retained sweating in the central mask of the face, are necessarily the same as those concerned with gustatory sweating. This has been presumed, since both forms of sweating cannot be explained by the ordinarily accepted sympathetic pathways from the thoraco-lumbar outflow. The anatomical pathways are so complex in this region that it is unlikely that particular pathways to the central part of the face could be demonstrated by dissection or by the examination of microscope sections of human foetuses. Such pathways must exist and evidence relevant to either explanation has been discussed. The association of sweating retained in the perineum as well as that retained in the central part of the face has provided a strong inference that these two may be associated and that the cranio-sacral outflow of the parasympathetic may be in part responsible. Here some sacral parasympathetic efferents may establish synapses with a few postganglionic cells in the lower sacral segments.

SUMMARY

¶ Gustatory and retained facial sweating after stellate ganglionectomy is maintained by a nervous pathway.

¶ There is much evidence to suggest that this pathway may be via the facial (VII) or glossopharyngeal (IX) or both cranial autonomic nerves. Attention is drawn to the retained area of sweating in the perineum after lumbar ganglionectomy, which is possibly maintained via the sacral autonomic nerves.

¶ If, however, all facial and gustatory sweating is maintained by sympathetic nerves, these nerves leave the spinal cord above the ciliospinal outflow in T.1 and T.2 (or even C.8) spinal nerves, or possibly they ascend in the neck other than in the cervical sympathetic chain via the vertebral nerve, sinuvertebral nerve or along the carotid arteries. It is also possible that they may pass, through preganglionic fibres leaving the upper cervical segmental nerves, directly into the cervical intermediate ganglia.

¶ The epibranchial placodes associated with the V, VII, IX and X cranial nerves are derived from areas of ectoderm whose subsequent development would provide areas of skin remarkably similar in pattern to those areas where sweating is retained on the face after sympathectomy: gustatory sweating in the normal subject is observed most frequently in these areas.

¶ It has been shown experimentally in cats that after preganglionic denervation of the superior cervical ganglion, collateral sprouts from the adjacent vagus nerve will establish functional synapses with 'sympathetic' ganglion cells in the superior cervical ganglion. Similar evidence is available for man. Such a pathway would readily explain the occurrence of gustatory sweating after sympathectomy. It is probable that similar pathways could be established from the glossopharyngeal and facial nerves to sympathetic ganglion cells distal to the superior cervical ganglion and lying at the base of the skull, in the petrous and infra-temporal regions.

¶ It is suggested that if such pathways can occur as a result of injury. they may also arise during development and thus supply the sweat glands in the central part of the face and larynx regions with autonomic pathways which are independent of those from the thoraco-lumbar outflow of the sympathetic.

¶ Similar connections between sacral autonomic fibres and ganglion cells in the lower sacral segments would account for the sweating that is retained in the perineum after thoraco-lumbar sympathectomy (as suggested by Monro, 1954*b* and 1956).

Part Three

VASOMOTOR CONTROL AFTER SYMPATHECTOMY

Chapter 12

§1. THE EFFECTS OF SYMPATHECTOMY ON VASOMOTOR INNERVATION AND ITS RECOVERY

HISTORICAL INTRODUCTION

ALTHOUGH Claude Bernard in 1851, when he first described the effects of sectioning the superior cervical sympathetic chain in the dog, the horse and the rabbit, believed that the resulting vasodilatation was primarily due to the increased metabolism of the tissues, he later (1858—*pages 240–241*) realized correctly that it was really due to the release of vasoconstrictor tone consequent on sectioning sympathetic fibres. From this time onward many physiologists have performed experiments on the effect of cutting and stimulating different branches of the sympathetic nervous system, and have observed its invariable constrictor effect on all blood vessels to the periphery. Langley (1891*a* and *b*) found that in the cat the sudomotor and vasomotor effect obtained on stimulation of nerves, ganglia or grey rami agreed very closely in their distribution. He showed that stimulating the sympathetic ganglia in the appropriate regions always produced constrictor effects on the blood vessels to the feet. Although he does not appear to have used a plethysmograph at this time, he refers to the as yet unpublished observations of Bayliss and Bradford who were using such apparatus on dogs. These workers first showed (1894) that the fluctuations in leg volume depended on vasomotor tone, since they disappeared after cutting vasomotor nerves. Such techniques were, by this time, in common use, and as early as 1886 Ellis had devised a micro-plethysmograph recorder for observing the fluctuations in limb volume of frogs and the pulse wave in the finger of man. Fluctuations in blood pressure not associated with pulse or respiratory cycle were first described by Traube in 1865 and by Hering in 1869. Bayliss and Bradford realized that the fluctuations in leg volume must be due to the same cause. An account of the early use of the plethysmograph is given by Barcroft and Swan (1953); this includes a description of the method of measurement and calculation.

Hewlett and van Zwaluwenburg, who in 1909 applied the venous-occlusion plethysmograph to the limbs of man, showed that these rhythmic fluctuations in blood flow were due to changes in vasomotor tone. In this technique there is no hindrance to the arterial inflow to the limb in the plethysmograph provided that the collecting cuff

pressure is not inflated above diastolic blood pressure. Two years later (1911), in a paper written with Marshall, they showed that in man the blood flow in a limb increased with an increase of the temperature of the water around the part.

The surgical implications of these discoveries do not appear to have been realized in this country for some years. Jaboulay in 1899 appears to be the first who realized the potential value of sympathetic interruption in vasospastic disorders, and his pupil Leriche was recommending periarterial sympathectomy in 1913. Further anatomical investigations were made by Kramer and Todd (1914) and Potts (1914) who demonstrated that the vasomotor innervation to the skin arterioles corresponded to the innervation of the somatic segments.

Royle (1924*a*), who was performing sympathetic ramisection for spastic paralysis, observed that coldness and sweating of the skin disappeared after regional sympathectomy and suggested a new approach to the treatment of vasospastic diseases of the extremities. Following this, Adson and Brown (1925) reported the treatment of Raynaud's disease by lumbar ramisection and ganglionectomy and perivascular neurectomy of the common iliacs. By skin temperature observations they showed the resulting vasodilatation and relief of vasospasm.

Lewis and Landis (1930) gave a careful account of the effects of cervico-dorsal sympathectomy in two patients with Raynaud's disease. By skin temperature observations they showed that there was an initial vasodilatation, but that this was not maintained at the same level over the course of time. They also found that cooling of the body caused slight vasoconstriction of the supposedly sympathectomized limb, but they did not comment on this. They expressed a doubt that inhibition of a vasoconstrictor tone was the complete explanation of flushing of the skin. In the next year Lewis and Pickering (1931) provided further evidence to suggest that sympathetic vasodilator nerves were present in man. This hypothesis has been argued on many occasions before and since, but Arnott and Macfie (1948), by calorimetric observations, showed that ulnar nerve block does not significantly alter the blood flow of the fifth digit in normal human subjects who have been brought into a condition of reflex vasodilatation. This was confirmed by Gaskell (1956 *b*), who showed that intra-arterial administration of atropine at the height of heating does not change the blood flow in the hand. Arnot and Macfie also showed that local cooling in the fifth digit, in reflexly dilated subjects, significantly reduces the blood flow, and that this reduction is not further altered by ulnar nerve block. Their latter conclusion confirmed Lewis's (1929) observations on the pulse volume in normal fingers and in cases of Raynaud's disease. In severe cases of this malady an increase of the pulse volume did not begin until the temperature of the water around the finger had reached about 30° C.,

but in normal subjects it starts to increase at about 20° C. and increases progressively for each 5° change in local temperature.

Lewis (1930) had shown, however, that when normal fingers are placed in very cold water they respond by periodic vasodilatation, and that this phenomenon appeared to be the result of a local change and not an effect of central vasomotor control. Grant and Bland (1931) confirmed these observations in man and also on the bird's foot. They suggested that the greatly increased blood flow through the tissues of the digit was principally through arteriovenous anastomoses. These had first been described by Hoyer (1877) and Sucquet (1862), with a fuller account given of their occurrence in man by Grosser (1902). Grant and Bland made counts on the numbers of these specialized vascular shunts and found that they were much greater in the fingertip than in the middle phalanx, and more frequent here than in the proximal phalanx. They were relatively rare on the dorsum of the hand. Pickering (1932) reviewed the vasomotor regulation of heat loss from the human skin in relation to external temperature. He found that the application of cold to the skin produced reflexly a vasoconstriction, but that application of heat to the skin did not produce vasodilatation reflexly although it may cause vasoconstriction if the stimulus is excessive. Cool blood returning from the skin that is cooled induced a reflex vasoconstriction by a central mechanism. Similarly, any vasodilatation produced is due solely to the action of the central mechanism excited by a rise of blood temperature. This was confirmed by Gibbon and Landis (1932), but Kerslake and Cooper (1950) showed that a nerve reflex was also involved and that it did not occur after sympathectomy.

More recently both Roddie, Shepherd and Whelan (1956 and 1957*a* and *b*) and Edholm, Fox and Macpherson (1956 and 1957) have shown that in the skin of the forearm vasodilator nerves exist and that they are cholinergic in character (Roddie *et al.*, 1957*b*). These papers were based on results obtained on venous occlusion plethysmography combined with local anaesthesia of nerves or after intra-arterial atropine, provided it was infused before body heating was started. They both confirm the earlier report of Grant and Holling (1938), whose observations were based on skin temperature. Both Roddie *et al.* (1957*b*) and Edholm *et al.* (1957) consider whether this vasodilatation could be brought about by a bradykinin-forming enzyme (Hilton and Lewis, 1956 and 1957), since Fox and Hilton (1957 and 1958) have recovered this substance from human forearm skin during body heating. Edholm *et al.* (1957) seem to be more in favour of this mechanism than Roddie *et al.*, and it should be remembered that in the case of the salivary gland, bradykinin-forming enzyme is still released on stimulating the chorda-lingual nerve after atropinization (Hilton and Lewis, 1957). Both groups of workers agree, however, that in the hand the dilator response is due

solely to the release of vasoconstrictor tone. This may be a little puzzling, as the skin of the hand is also freely supplied with sweat glands. Since Roddie *et al.* (1957*b*) found that infusion of intra-arterial atropine, at the height of sweating did not alter the forearm blood flow they repeated Gaskell's work (1956*b*) by infusing atropine before heating and concluded that, although they could not exclude dilator nerves in the hand, the part played by them must be small.

Freeman (1935) investigated the effects of temperature on the rate of blood flow in the normal and sympathectomized hand. He used a water-controlled hand plethysmograph and found that in the normal there were variations of blood flow up to 100 per cent., but these were nearer 20 per cent. in favourable cases. He considered that the errors would be minimized if the mean of five consecutive readings were taken. Reduction in blood flow could also be produced by noise, discomfort or embarrassment, as well as by cold. In the sympathectomized hand these spontaneous variations in blood flow were absent, but with an increase in temperature there was a slight increase in blood flow which was much less than on the normal side. Freeman confirmed the observations of Thomas (1926) and Lewis and Landis (1930) that the application of cold would still cause slight vasoconstriction in the sympathectomized hand. It now appears, however, that sympathectomy could not have been complete in all the cases these workers examined; indeed, Freeman's observations were performed on a case two years after operation. Freeman stated that heating the body produced no vasodilatation in the sympathectomized hand, but actually his figures (*Fig. 6*) show that there was a slight decrease in flow—the time-interval since operation was not stated. This decrease occurred even if the local temperature remained constant. Procaine block on the sympathectomized hand caused an increase in flow when the hands were placed in cold water at 17° C. On warming the body ten days after sympathectomy, there was a very slight increase in the blood flow in the hand; but after six months there was a considerable increase in blood flow from a lower basic level (*Fig. 9*), i.e. probably re-innervation had taken place. Freeman suggested that in the sympathectomized hand the increase in blood flow with local temperature increase could be explained by chemical control by metabolites according to the Arrhenius' equation: this states that the logarithm of the rate of a chemical reaction is proportional to the reciprocal of the absolute temperature. It now appears that in regard to the rate of blood flow, such a relation, if any, was probably entirely fortuitous. Freeman suggested that the vasoconstriction in sympathectomized hands on cooling the body was due to adrenaline sensitization. In earlier papers with Smithwick and White (1934) and Smithwick, Freeman and White (1934) he had investigated the effects of intravascular adrenaline on the skin temperatures of the

fingers and on the rabbit's ear. The sensitivity of various tissues to adrenaline after sympathectomy had first been shown by Elliott (1905) and Meltzer and Auer (1904*a*). Unfortunately, however, Freeman *et al.* (1934) and Smithwick *et al.* (1934) had misread these earlier workers, and had ascribed a potentiation of the effects of adrenaline on only postganglionic and not preganglionic denervated vessels. They thought, if section of the preganglionic fibres alone were performed, vasoconstriction to circulating adrenaline would be less pronounced. Smithwick (1936) therefore introduced a new form of sympathectomy which he claimed would provide only a preganglionic section of the sympathetic pathways concerned with the blood vessels of the hand. It has been shown earlier in this monograph why such an operation is unlikely to produce the effects claimed for it (Fig. 22). Simmons and Sheehan (1939) did not consider that adrenaline hypersensitivity was likely to be the principal cause of 'relapse' after sympathectomy, since it was at a maximum only eight to ten days after operation. Telford (1935) had devised a similar operation to that of Smithwick for much the same reasons. There has been considerable discussion on this vexed question of the apparent relapse of the vasomotor denervations following sympathectomy, and the whole subject will be discussed again later. The more recent conclusions of White, Smithwick and Simeone (1952), (*page 109*), however, were that regeneration of the sympathetic nerves or the less likely functional reorganization of neurones, as suggested by Geohegan and Aidar (1942), was a more probable cause of this relapse than any supersensitivity to adrenaline following denervations. The more recent reports of Monro (1954*a* and *b*) and Murray and Thompson (1957*a* and *b*) support the latter view.

Further contributions to the technique of investigation of vasodilatation and vasoconstriction in response to warming and cooling the body have been made by Uprus, Gaylor and Carmichael (1936). They have drawn particular attention to the local temperature of the limb, its posture, and the rapidity of the rise of blood temperature, which they said could best be produced by immersing part of the body in hot water, rather than by means of a hot-air cabinet. Wilkins, Doupe and Newman (1938) adapted the plethysmographic method of Hewlett and van Zwaluwenburg (1909) to the estimation of the rate of blood flow in normal fingers and the changes in response to local temperature differences. They showed that body warming may increase the blood flow in the fingers by as much as 100 times, though other workers have shown that in the hand it rarely exceeds a third of this. The increase in blood flow resulting from local heating of the finger is not as great as that produced by body warming. The blood flow to the terminal phalanx of the finger is considerably greater than that to the middle phalanx when the vessels are dilated, though this varies in

different individuals. They estimated that the flow in the terminal phalanx was usually three times as great as that in the middle phalanx. In obtaining their estimations they measured five consecutive readings and averaged them—variations in these readings were greater before warming the body. Other precautions which they found to be necessary for accurate observations were to avoid measurements after reactive hyperaemia and to place the collecting cuff as close as possible to the plethysmograph cup. For sealing the finger they used Vaseline, which offered no compression to the finger tissue.

Grant and Pearson (1938) confirmed that the blood flow in the fingers was much greater than that in the hand, and this again was greater than that in the forearm. This, of course, was in keeping with the counts Grant and Bland had made (1931) of the frequency of the occurrence of arteriovenous anastomoses in human skins at different sites.

Lewis (1938) again drew attention to the observation that the full vasodilatation resulting from sympathectomy declined during a period of about a week. More recent interest in this problem has been shown by Barcroft and Walker (1949), Walker, Lynn and Barcroft (1950) and Barcroft (1951 and 1952). The author's contributions to the subject will be discussed later.

A further critique of the venous-occlusion plethysmographic method of measuring blood flows in the extremities of man has been given by Landown and Katz (1942). In addition to the precautions stressed by Uprus *et al.*, Landown and Katz showed that attention must be paid to the collecting cuff pressures, and investigated this in relation to the displacement artefact at the start of a recording. A truly rectilinear record was much to be desired, and they showed that for the most accurate results the limb should be at or just above the level of the heart. Gaskell (1956*a*) has considered these matters further in relation to the size of the cuff and collecting pressure.

Greenfield and Shepherd (1950*a*) showed that the venous-occlusion plethysmograph when applied to the fingers immersed in cold water was an unreliable method of estimating blood flow, since the size of the pulsation indicated a larger flow than was shown by the slope of increase in volume. They considered that this was due to cooling causing a constriction of the capacity vessels in the finger, but that when the temperature was raised to 32° C. the capacity vessels relaxed and flow readings became valid. They therefore adapted the method of calorimetry to measure blood flow on a standard length of finger at low temperatures. They realized that it was of little use expressing blood flow in relation to a standard volume of the fingertip, if, as Wilkins, Doupe and Newman (1938) had shown, the rate of maximal flow was much greater in the tip than in the middle phalanx. Although the rate of

blood flow could be expressed in relation to the volume of finger on which it was measured, for comparative purposes this would be valueless except for a finger of exactly the same dimensions. Greenfield and Shepherd showed that immersion of a finger in a bath 0°–6° C. caused an initial, almost complete, cessation of blood flow, followed after 5–10 minutes by a rapid increase to 30–98 ml. per 100 ml. per minute. This subsequent behaviour during one hour of immersion varied between individuals, most showing a general decline with intermittent periods of greatly diminished flow. Similar but smaller changes followed initial constriction at 6°–12° C., but at 12°–15° C. there was no initial constriction, although flows were generally lower than in the two preceding ranges. Carmichael (1950), in a review of the digital vasomotor responses, believed that peripheral sympathetic fibres constrict the blood vessels on the arterial side of the vascular bed. This can be initiated reflexly by both visceral and cutaneous sensations, and these reflexes are obtainable at spinal levels—ipsilateral with minimum cutaneous stimuli, and bilateral with stronger stimuli. He believed that vasodilator fibres were present but not so definitely, and that veins have constrictor fibres only.

Greenfield, Shepherd and Whelan (1951) investigated with their calorimetric method the proportion of total hand blood flow passing through the digits. They confirmed the earlier observations of Wilkins *et al.* that the flow in the fingers was relatively much greater than that in the hand, but found that when a subject is comfortably warm a greater percentage (average 69 per cent.) of the total hand flow passes through the digits than when he is cool (average 43·8 per cent.) or indirectly heated (44·5 per cent.). They also found that the digital vessels appeared to dilate at lower levels of general body heating than do those of the body of the hand, and that the fluctuations in the blood flow occurred synchronously in the hand and all the extremities.

CRITERIA FOR TECHNIQUE OF DIGITAL PLETHYSMOGRAPHY

A study of the above literature suggested that digital plethysmography can provide a convenient method of determining the presence or absence of vasoconstrictor innervation after sympathectomy and that this might be a more sensitive method than hand or foot plethysmography. Precautions would need to be taken in regard to the absence of constriction at the base of the finger by the plethysmograph cup, the comfort and position of the limbs, the absence of external stimuli and control of temperature. The claim, by some workers, that vasodilator fibres are present in the limbs might be more easily investigated on cases in which vasoconstrictor tone had been removed as a result of sympathectomy, provided that such vasodilator nerves, if they exist, did not pass through the sympathetic chain. Although it is possible that

different individuals. They estimated that the flow in the terminal phalanx was usually three times as great as that in the middle phalanx. In obtaining their estimations they measured five consecutive readings and averaged them—variations in these readings were greater before warming the body. Other precautions which they found to be necessary for accurate observations were to avoid measurements after reactive hyperaemia and to place the collecting cuff as close as possible to the plethysmograph cup. For sealing the finger they used Vaseline, which offered no compression to the finger tissue.

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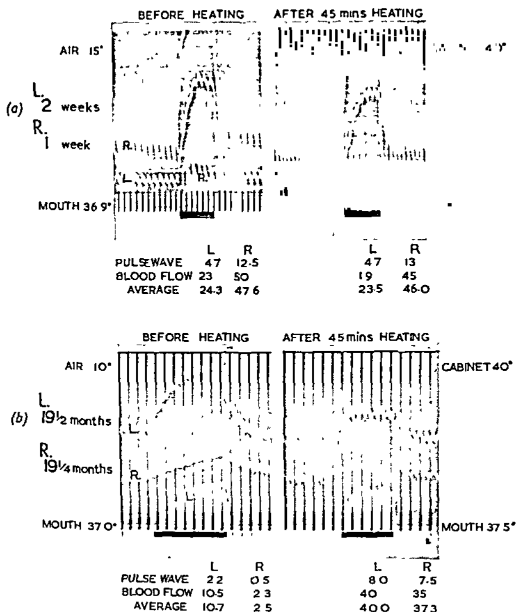


Fig. 64. Blood flows in normal fingers.

better release of vasoconstrictor tone would be attained by immersion of the opposite extremities in hot water, this method became impracticable if it was also intended to observe sudomotor activity over the whole body. All these criteria have been considered in the construction of the plethysmograph designed by the author, and in the method of carrying out the observations.

TECHNIQUE AND METHODS OF DIGITAL PLETHYSMOGRAPHY

The first account of a practical micro-volume recorder seems to be that of Ellis (1886). This had the advantage of producing a linear trace with almost no pressure changes. He recorded the movements of a drop of fluid in an horizontal tube and found that for the finest tube ether was the best liquid, but for larger tubes, of barometer bore, alcohol or water were sufficient. The horizontal tube was held in front of a slit in the wall of a dark room and illuminated by the sun from a mirror. A greatly magnified image of the meniscus, at one end of this column of fluid, was projected by a photographic lens on to photographic paper or film moved by clockwork in a vertical plane. With this apparatus he examined the form of the pulse wave in man.

Johnson (1932) utilized a similar method for observing the changes in peripheral circulation following cervico-dorsal ganglionectomy. He used alcohol because of its low viscosity, specific gravity and surface tension, but coloured it with a dye so that a better contrast was obtained on a photographic record. With this apparatus he observed the skin temperature and digital pulse wave, each day after operation, and found that whereas it increased to 5 units immediately after operation and for the next two days, it declined to 3 units on the third, to 1 on the ninth, and by the thirteenth day was back to its preoperative level of 0·5 units. Bolton, Carmichael and Stürup (1936) adapted the rubber diaphragm principle for the measurement of small changes in volume. A small optically flat mirror was mounted on the tambour, and by this means a light beam was deflected on to photographic recording paper. Several such units could be recorded simultaneously.

Turner, Burch and Soedman (1937) used a mechanical type of plethysmograph working on the bellows principle for studies on the pulse and blood volume of the fingertip. With it they were able to show that raising the arm caused an increase in the pulse volume with a decrease in total finger volume, whereas lowering the arm below heart level caused the opposite in both.

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compared his estimations in the digits with those obtained from simultaneous venous-occlusion plethysmography. The reports of other

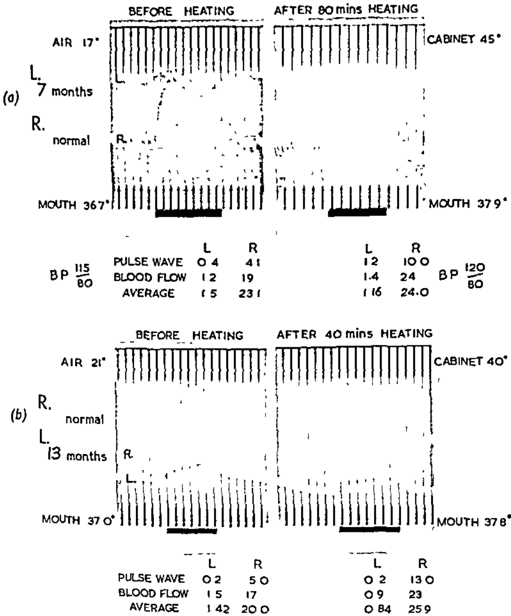
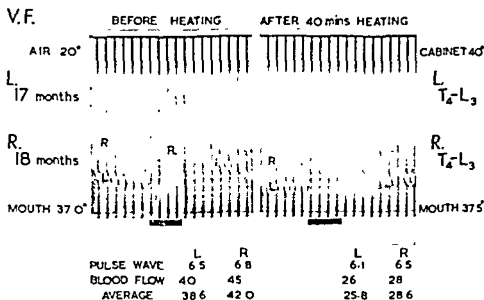


FIG. 66. Blood flows in fingers after brachial plexus lesion. Shows decrease in blood flow after general body heating.

THORACO-LUMBAR SYMPATHECTOMIES



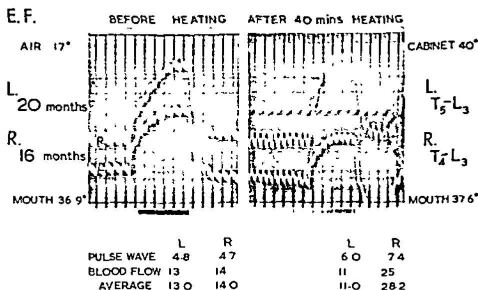


FIG. 65. Blood flows in toes after thoraco-lumbar sympathectomy. Shows decrease after general body heating.

observations performed with these techniques have been made by Hertzman and Dillon (1939*a* and *b*, and 1940*a*, *b* and *c* and Hertzman, Randall and Jochim (1946).

Goetz (1939) described a displacement liquid plethysmograph on the Ellis principle, which he later (1946) incorporated into a relatively portable unit. In a paper with Ames (1949) he gives an account of the various precautions to be taken with this instrument in regard to position of the limbs, etc. He had now modified his apparatus so that records from both index fingers or from both great toes could be taken simultaneously. In two other papers (1948 and 1949) Goetz describes the use of this instrument in the diagnosis and treatment of vascular diseases. In a further paper (1950) Goetz shows that skin temperature measurements in the digits were not always proportional to the blood flow as measured by his plethysmograph. He also confirmed that slight changes in posture would produce a marked effect on the plethysmographic record. These changes were similar in the sympathectomized limb, but the temperature of this limb did not reach full normal vasodilator level although the plethysmograph showed full vasodilatation. More recently Felder, Russ, Montgomery and Horowitz (1954) agreed that temperature readings gave an accurate indication of toe plethysmograph blood flows only at low values. Burch (1947) utilized a small metal bellows which activated a pointer held in a watch bearing. The movements of the pointer were recorded photographically. With this he studied the fingertip and was able to recognize five types of spontaneous deflections in volume.

Greenfield and Shepherd (1950*b*) described a water-controlled. plethysmograph in which the finger was inserted into a finger-stall surrounded by water in a sealed chamber and stirred with a magnetically activated paddle. In their apparatus, however, a head of water of several centimetres was required to keep the finger-stall closely applied to the finger.

The author's plethysmograph to be described later, was first built in 1949. It has many points of similarity with the Goetz apparatus, but has been constructed of materials easily available in the workshop and has proved to be far less costly. An added refinement in the optical system has provided a very efficient light source from an ordinary mains electric bulb, and by slight variation of the vertical displacement of the optical axis, the records from the two sides of the body may always be easily distinguished.

A new pattern of venous-occlusion plethysmograph, using a transducer valve and electronic circuit, has recently been described by Melrose, Lynn, Rainbow and Wherrell (1954). This seems to have no advantages over the author's apparatus except a better frequency response. Although the sensitivity is rather greater, this is not reliable

This feature of a reduction of blood flow in the digits after heating the patient was relatively frequent and will be discussed fully later.

Fig. 66 (*a*) (E.C.) shows the records obtained at the earlier examinations on the case of brachial plexus lesion. On the right side the record is at all times normal, although it shows a slight irregularity in the top left record. At seven months the left record shows a very small pulse wave and a correspondingly small blood flow. After eighty minutes' heating, however, the pulse wave has increased in size, but the rate of blood flow has decreased slightly. On the right side it is evident that it is very difficult to estimate fast flows after heating the patient, since the venous spaces are filled by two pulse waves. It is probably that the actual blood flow is much greater than that indicated.

When examined again thirteen months after injury (*b*), it will be seen that the record from the left side shows very small pulse waves but a slightly greater flow than that at the first examination. The air temperature at the time was, however, 4° C. warmer. After heating the patient the rate of flow on this side decreases slightly but the pulse wave remains relatively unchanged, though probably it is too small to have any significance. Again it will be seen that on the normal side there is great difficulty in estimating the fast rate of blood flow.

This case represents an apparently complete denervation of the vessels of the hand at this stage, and it is interesting to observe that decrease of blood flow after heating is also found in such a case.

CONDUCT OF TESTS

Fig. 67 shows a composite graph of various observations made during the tests for vasomotor and sudomotor control, eight days after stellate and T.2 ganglionectomy (left) performed on the one case of known normal vessels—hyperhidrosis of hands (F.MC.C.).

The patient lay exposed on the bed in the heating cabinet covered only by pyjamas. The temperature of the surrounding air was about 12° C. Half an hour was allowed for full vasoconstriction to be produced on the normal (right) side; the mouth temperature was 36 8° C. Thermocouples were attached to the index fingers inside the cups and also to the adjacent fingers (not recorded on the graph). Initial temperatures were 35° C. on the right and 19·5° C. on the left. On this graph, on the left (operated) side all points are indicated with solid centres, whereas those on the unoperated side have open centres. When the skin temperatures appeared to have reached constant values, blood flow estimations were made and the averages are plotted.

Left. Blood flow 38 0.* Pulse wave 6 6.*
Right. Blood flow 1·6. Pulse wave 1·0.

The cabinet was then closed and the radiant heat turned on. The temperature inside the cabinet rose gradually from 12° to 40° C. over the next 1½ hours. The temperature of the air in the neighbourhood of the hands, which were outside the cabinet, only rose from 15° to 18° C. (about 3° C. in all). After forty-five minutes' heating, blood flow observations were again determined. The skin temperature on the right index finger had begun to rise after about ten minutes, and after thirty minutes had reached 34° C.

Left. Blood flow 40. Pulse wave 7·3.
Right. Blood flow 33. Pulse wave 10.

After a further 15 minutes' heating, the temperature of the right finger had slightly surpassed that on the left. Plethysmographic observations showed:

Left. Blood flow 42. Pulse wave 7·3.
Right. Blood flow 28. Pulse wave 16·5.

The effect of placing the left hand in cold water was then tried, since observations on another patient had indicated that this caused an increase in flow. Unfortunately,

* For expression of these values see p. 203, *Columns* 16 and 17, 21 and 22.

below 1 c.mm., which is the same sensitivity as that of the author's. The range is only half that of the author's apparatus. Considerable complexity is introduced by the electronic circuit, and photographic recording is required for both techniques.

METHOD AND OBSERVATIONS

A description of the author's apparatus and the method of evaluating the record and calculating the result is given in the Appendix. It will be an advantage, however, to consider certain illustrative records at this stage in order to gain an idea as to the amount of information furnished by the plethysmographic record.

Fig. 64 (*a*) shows [illegible] after bilateral stella [illegible] only case observed [illegible] normal blood vessels. In the top records may be seen the specimen observations obtained respectively before and after heating the patient. Although five or six actual observations were made on each occasion, only the record of one of these is illustrated. It will be observed that although the pulse waves before and after heating are relatively unchanged, the pulse rate is much increased after heating, also that on the side tested only one week after operation the pulse wave is very much larger. The slopes of the record when the venous occlusion cuffs are applied show a slight decrease in flow after heating—this, however, is not statistically significant. It will also be observed that the volume of the venous spaces is very slightly decreased after heating, indicating a possible venoconstriction.

The lower records (*b*) show specimen observations obtained when the patient was examined at nineteen months after operation. Before heating, the pulse wave is much smaller on the right than it is on the left but, after heating, they are both increased to approximately the same level. This indicates that greater vasoconstrictor control must have been present on the right side initially. Similarly, the slopes of the pulse waves when the venous occlusion cuffs are applied indicate a greater initial blood flow on the left side, whereas, after heating, both are at about the same rate. It is not possible to comment accurately on the size of the venous spaces, but it would appear that after the second examination they are little different before and after heating

It is therefore evident that in this case of sympathectomy on normal vessels vasoconstrictor control was abolished shortly after operation, but a great deal of this had been regained at a subsequent examination—especially on the right side.

Fig. 65 shows records obtained from a case of thoraco-lumbar sympathectomy. In the upper record it will be observed that after heating the patient there is a slight decrease in the pulse volume on each side and a highly significant decrease in the rate of blood flow on each side. It is also apparent that the venous spaces are filled with fewer pulse beats and that these pulse waves themselves appear to be smaller after heating. The venous occlusion spaces must have been reduced after heating. It is unlikely that this could be accounted for by the position of the plethysmograph cups having been altered and less tissue enclosed after heating, since there is such a small reduction in the size of the pulse wave.

The lower records show another case in which blood flows were measured in the toes after thoraco-lumbar sympathectomy. It will be observed that the pulse waves are slightly increased on both sides after heating, but that the blood flow on the left side is slightly but significantly decreased, whereas that on the right, which was initially larger, has shown an increase. It would appear, therefore, that vasoconstrictor control has in part returned to the left toe. Again it should be noted that the venous spaces on the left side are slightly reduced after heating, and that this is the same side as shows a slight reduction in flow.

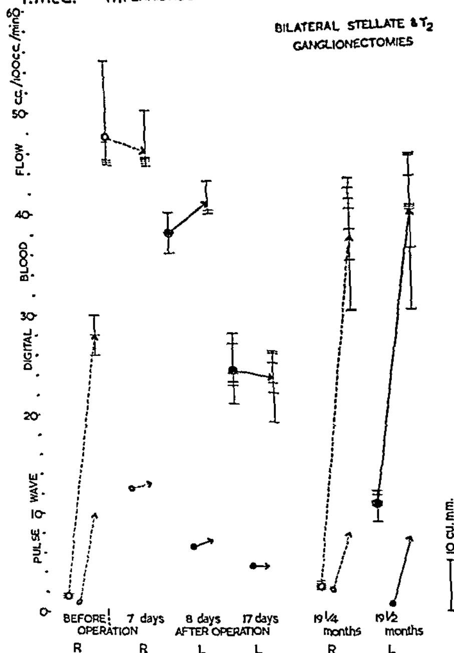


Fig. 68. Case F.McC. Blood flows and pulse waves at intervals after operation in a case with normal fingers.

obtained after heating by that obtained before heating, when maximal vasomotor control should have been effective. If no vasomotor control is present, the index should be approximately unity, but if much control is present, as on the normal side, then the index should be well above unity. Although the volume of the index fingers in this patient were each 10 c.c. on each side, this was not always so in other cases. The expression of the relative change in flows as an index avoids any inaccuracy. In this test the values were:

Heating index: Blood Flow, left 1·08; right 17·4.
Pulse, left 1·15; right 16·5.

however, the change in position of the hands caused the plethysmograph cup to become displaced and subsequent observations on the blood flow could not be read accurately. The pulse wave, however, was increased to 10 on the left side. The tem-

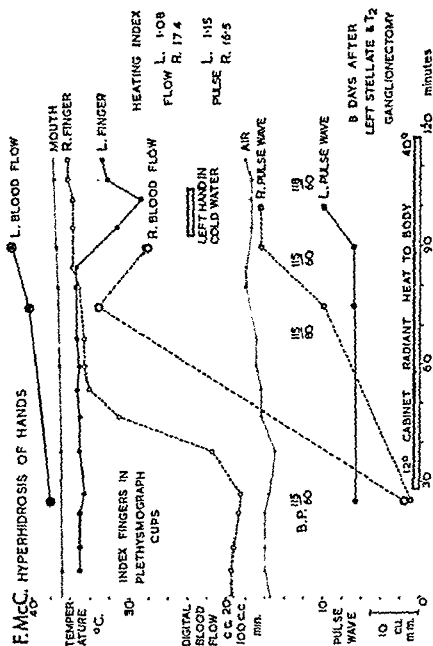


Fig. 67. Case F.McC. Recording of skin temperatures, blood flows and pulse waves during general body heating in a case with normal fingers.

perature of the finger in the cup had dropped to 29° C. and ... 32·5° C.

Observations ... except for ... The mouth temperature h... of the test, when the radiant heat was turned off.

From these figures were calculated the heating indices for blood flow and pulse wave. This calculation is performed by dividing the average of the measurements

Usually this was continued until the patients mouth temperature rose at least 1° C., or reached 37·4° C.

14 Indicates whether fingers or toes were examined. After four-quarter sympathectomy, observations were made on fingers or toes on different occasions.

15 Indicates the reference number for each observation and is marked beside each relevant point in graphs of blood flow and pulse wave heating indices (Figs. 69 and 70). These points are marked in black with white numerals for fingers and clear circles with black numerals for toes. The table should therefore be read against the symbol F or T, the reference numbers for T being in bold numerals, as the same number may apply to both. The orders of these points are taken from the convenient positions on the plots of the graph of the blood flow heating index.

16 and 17 Show the mean blood flows expressed as if 10 c.c. of digit were included in the plethysmograph cups. This was not exactly so in all cases but, as has been explained earlier, it would be inaccurate, since blood flow along the digit is not proportional to its length. As it has been shown that the blood flow in the terminal phalanx is about three times greater than that of the middle phalanx, it is obviously of better comparative value to measure standard lengths of the phalanges, which are taken for the distal two phalanges of the finger or terminal phalanx of the big toe.

18, 19, 20 Refer to statistical examination of the observations. The 't' test has been applied to all observations and the probability is taken from standard statistical tables. Statistics were calculated according to the method recommended by Bernstein and Wetherall (1952).
If the probability is better than 0·05 (5 per cent.) it is regarded as significant;
If better than 0·02 (2 per cent.) it is regarded as more significant;
If it is better than 0 01 (1 per cent.) it is regarded as highly significant and many of these points are better than 0·001, or very highly significant (1 in 1000).

21 and 22 Show the height of the pulse wave measured in mm. on the record. 1 mm. ≡ 2 c.mm. expansion. The pulse waves were measured on portions of the graph showing no general change in volume and, after heating, were usually measured at a faster speed of recording. Patients showing evidence of cardiac disease occasionally show irregular heights of pulse wave, and on these cases the observations were averaged.

23 and 24 Show the indices for blood flow and pulse wave. These are expressed as the flow (or pulse wave) after heating, divided by that obtained before heating. In this way the actual volume of the digit enclosed in the plethysmograph is of no account since it is unchanged before and after heating.

25 Shows the correlation (if any) between the blood flow and pulse wave heating indices. That for blood flow has been divided by that for pulse wave. The significance of this column will be discussed later.

26 Shows notes of any particular observations.

Attention is drawn to the observations made on hot days when there was probably only partial vasoconstriction before heating. This would make the heating index lower than it should have been, but as no constant temperature room was available it was impossible to produce full vasoconstriction on these occasions. HLZ indicates a case who was receiving the adrenolytic drug hydrallazine which produced an unusual change, in that the pulse waves were very large and decreased on heating. It is therefore thought that they should not be included with the other observations,

There is thus considerable agreement on this occasion but, as will be seen from Table IX, this is not always the case.

The observations obtained on this occasion and on subsequent occasions up to nineteen months are plotted in the graph, Fig. 68. As in the previous graph the points with solid centres are those obtained on the left side, and the changes observed before and after heating are connected by continuous arrows. Those on the right side have points with open centres and are connected by arrows with dashed lines. The blood flows before and after heating are plotted as actual values (cross lines) at each observation, and as the average by the arrow. The pulse waves are plotted simply as arrows with initial points and apices indicating the pulse wave obtained after heating. It will be observed that on the right side, before operation on this side, there is considerable initial vasoconstriction and that after heating (as in the experiment just described) the blood flow increases to about 28 and the pulse wave to 16·5.

Seven days after operation on the right side the blood flow, on that side, starts at about 48 and after heating decreases slightly to about 46. The pulse wave is only slightly changed—increasing from 12·5 to 13.

The observations on the left side eight days after operation have already been described, and at seventeen days after operation they show a *slight* decrease of blood flow from about 24 to 23·5, whereas the pulse wave is unchanged at about 4·7.

At nineteen months after these operations the initial blood flow and pulse wave on the right are almost the same as before operation; but after heating, the blood flow rises to a rather higher level of about 40, whereas the pulse wave is not so high at about 8. On the left side on the same occasion, the initial blood flow is greater at about 11, rising to about 40. The pulse wave on this side, however, is again small and increases from 2·2 to 8.

Considering the change in blood flows, therefore, it is evident that there is greater vasoconstrictor control on the right than on the left, nineteen months after operation, and that the range is comparable to that before operation, although the maximum blood flow never reaches as high a level as that observed soon after operation. The significance of these results will be discussed later in regard to recovery of vasomotor innervation after sympathectomy.

The observations on all cases upon whom plethysmography was performed have been tabulated in Table IX. For convenience in reading this table the following notes are given:

Column	*Data*
1	Initials of patients arranged in alphabetical order of their surname—for convenience in comparing their sweating patterns shown in Part I.
2	Age in years at time of relevant operations.
3	Side examined.
4	Levels of ganglionectomy, the upper being shown first. T = transthoracic resection.
5	Interval in months since the relevant operation.
6	Evidence of sudomotor activity in the hand or foot at the relevant examination. + = slight evidence of activity in limb. ++ = marked sudomotor activity in the hand or foot.
7 and 8	Mouth temperaures before and after heating the patient.
9 and 10	Temperatures of the air in cabinet before and after turning on the radiant heat.
11 and 12	Blood pressure of the patient in mm. of Hg., with the systolic pressure in bold type. It was not always convenient to measure the blood pressure, especially when observations were made on the fingers.
13	Time for which radiant heat was applied before observations were made.

D.F.	20	L T6 T R. T6 T	L3 L3	5¼ 3½	+ +	36 6	37 7	11	43	170 120	170 115	40	T T	12 32	7 5 6 1	29	11	19 245	0 0	3	. 9	4 5	1	2 55	
P.F.	33	L T.4 R. T4	L3 L3	21½ 23½	– –	37 1	37 6	24	37	200 130		40	T T	22 23	29 6 23	32·5 20 7	9 9	2 073 1·006	·1 ·4	8 8 7·1	9 0 7·1	1·1 0 90	1 02 1 0	1 08 0 90	HD
H.F.	47	L. Normal R St.		½	++	36 7	37 4	18	42			50	F F		1 8 3 2	53 0 38 4				1·3 2 0	12 0 8 0	29 5 11·9	9 2 4 0	3 21 2 98	
D.M.	22	L. Normal R. Normal				36 9	37 4						F F		6 0 2 1	36 6 3				1 0 0 5	7 8 4 3	6 0 3 0	7 8 8 6	0 77 0·35	
		L. St. R. St	T2 T2	½ ½	– –	37 0	37 5	17	42				F F	3 4	9 7 19 8	6 6 14 5	9 8	2·783 3 337	·05 ·02	3 0 4 2	1·2 4 3	0 68 0·74	0·40† 1 02	1 70 0 73	S lt.
		L. St R. St.	T.2 T.2	11½ 11½	++ ++	36 9	37 7						F F	29 21	1 4 16 5	3 5 20	10 10	10 272 2 725	·01 ·05	0 5 4 5	0 5 7 0	2·5 1 21	1·0 † 1 55	2 5 0 78	S.lt.
M.M.	26	L T2 R. T2	T3 T3	½ 4	– –								F F	10 20	24 8 9 4	39 0 13 5	8 8	5·477 5 214	·01 ·01	4 0 1 8	4 3 2 0	1·56 1 44	1·07 1·11	1·46 1 30	
F. McC.	29	L. St. R. Normal	T.2	½	–	36 8	37 3	16	40	125 60	125 60		F F	19	38 0 1 6	41 0 28	6	1 965	·2	6 6 1·0	7·3 16 5	1 08 17 4	1 10 16 5	0·98 1 04	
		L. St. R St	T2 T.2	½ ½	– –	36 9	37 3						F F	5 1	24·3 47 8	23 5 45 8	12 12	0 535 1 264	·7 ·3	4 7 12 5	4 7 13 0	0 97 0 96	1·0 1 04	0 97 0 92	
		L. St. R. St	T2 T.2	19½ 19½	++ ++	37 0	37 5	10	40				F F	31 30	10 8 2 5	40 37·4	13 13	12 583 14 782	·01 ·01	2 2 0 5	8·0 7·5	3 7 14 9	3 6 15·0	1·03 1 0	
M.P.	28	L. T.1 R Normal	root	½	++	37 2	37·3						F F		16 0 8 3	31 0 26 0				2 7 2 2	6 0 6 8	1·94 3 13	2 22 3 08	0·88 1·18	NC
E.P.	44	L. T4 R T4	L.3 L3	27½ 29½	– –	37 3	37 8	24	42				T T	17 24	10 1 11·3	28 6 12 8	11 11	16 387 1·331	·01 ·3	4·4 4 6	4·0 4·4	2 82 1·13	0 91 0 95	3·10 1·19	
W.S.	35	L T.10 R T4	L3 L2	40 42	– –	37 0	37 6	13	36	240 140	190 120	60	T T	30 20	47 0 18 5	47 0 63	8 8	0 0 12 229	·01	4·9 10	7 5 11	1·00 3 30	1 56 1·10	0 64 3 00	
B.S.	27	L. T9 R. T.8	L3 L2	56 57½	– –	37 2	37 9	19	40	180 130	180 130	45	T T	31 21	28 6 8 7	30 4 20 2	10 10	1·175 11 068	·2 ·01	3 5 6 5	6 5 6 2	1·06 2 32	1 85 0 96	0 52 2 41	
J.T.	36	L. T4 R. T.4	L3 L3	31½ 33½	– –	37 1	37 6	21	35	150 100	145 95	40	T T	25 27	13 4 30 8	16 8 31 3	11 11	4 904 0 241	·01 ·9	4·5 7 5	3 0 6 5	1·25 1·01	1·11 0 87	1·13 1·16	HD
F.T.	58	L. L.1 R. Normal	L.3	8	–	36 8	37·4		40				T T		5 3 8 9	11 0 18 8				1 3 2 3	1 8 6 5	2 07 2 1	1 39† 2 83	1·49 0·74	NC
		L. L.1 R. Normal	L3	4½	–	36 8	37 6						T T		0 72 0 24	2 5 13 0				2·5 1 5	2 5 13	3 47 54 0	1·0† 8·7	3·47 6 20	NC
		L. L1 R. Normal	L3	26½	–	36 7	38 2	17					T T		6 3 0 54	5·4 7 8				3 0 0 2	2 8 5 6	0 85 14 4	0 9 † 2·8	0·92 5·14	NC
		L. L1 R. Normal	L.3	33½	–	36 6	37·5	21	43				T T		8 4 3 7	14 0 12·3				1 8 2 0	2 2 9 2	1 67 3·32	1·22† 4 6	1·37 0 72	NC

For an explanation of the entries in each column, see pages 202–203.

but the mode of activity of this drug is interesting, and it is intended to make further observations on cases who are receiving it. NC indicates that for some particular reasons, usually peripheral vascular disease, the observations have not been charted on the graphs.

The collecting cuff pressure was 70 mm.Hg., which was usually well below diastolic blood pressure. It was reduced to 5 mm. below the diastolic when the latter was less than 70 mm.Hg.

The *blood flow heating indices* have been plotted graphically (*Fig.* 69) *on log.* paper against time (which is not strictly proportional and has been spaced out more for observations made shortly after operation). The points indicating observations on the same digit have been connected by continuous lines. Only two such points are indicated on the toes and these are connected by dashed lines. Fingers are shown in black with white numerals and toes by clear circles with black numerals as in columns 14 and 15 of Table IX. The observations on the case of brachial plexus lesion are indicated by the letters A, B, C, and are connected by a dotted line. In some cases observations were made before operation, usually at the time of the first observation after sympathectomy on the opposite side. It will be noted that there are relatively few points plotted for toes during the first year. This was because the significance of observations on the toes was not immediately recognized, and also because of the difficulty of performing plethysmographic observations on the first cases to be tested.

Observations on the Fingers

Up to time of three months after operation, many fingers show incomplete resection, *others again are relatively unchanged, and five cases (6 points) show a significant* decrease in the blood flow heating index. Observations carried out after three months, however, with the exception of the brachial plexus lesion, show only 1 point (F.24–22 months) which does not show a significant increase in the heating index. Many of them, such as points F.29–F.38, show very large heating indices. Other points, however, such as F.20–F.28 (except F.24), all show a significant increase, but to a less degree. It is therefore apparent that vasomotor tone may not always be absent even shortly after sympathectomy, but that cases examined in this series, at intervals greater than three months, invariably (with one exception) show presence of vasomotor control in the fingers.

Observations on the Toes

It will be evident that a few cases examined within about six months show incomplete resection of vasomotor innervation. These are points T.9–T.13, though points T.10 and T.11 are not significant. Point T.1 shows no change. After three months, however, it will be seen that by far the greater majority show no change or a slight decrease in the heating index. Points T.2–T.6 show a significant decrease; points T.17–T.21 show a significant increase, as also do points T.14–T.16 with T.25, although these are to a lesser degree. Points T.33 and T.34 are shown on this graph to show blood flows in the toes at six months. All other points examined after three months have an index of approximately 1, indicating no significant change, and statistically may be regarded as a single group. (Finger points F.27 and F. 28 show a significant increase, though this is less than observed in other such cases. This case, however, was examined *on a hot day and it is probable that the index would have* been greater if more vasoconstrictor tone had been induced at the start of the test.)

Peripheral Nerve Lesion

The only exception to the above conclusions is the case of brachial plexus lesion. Although examined as late as seven and thirteen months after injury, the heating index was significantly less than 1 (approximately 0·6) on each occasion, indicating a marked decrease after heating (Points A and B). At thirty-one months, however

; on the same occasion
ence of the hand. The
5 toes, as well as in this
case of brachial plexus
ulse waves were always

nilar fashion in Fig. 70.
ts F.3 and F.8 and toe-
. less than 1). In finger-
shortly after thrombosis
F.8) there was probably
oint T.11 is not immedi-
significant increase. The
n not all vasomotor tone
al sympathectomy. After
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th finger-points F.20 and
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lie very close to unity—
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and T.31, which show a
indices. From the general

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n that of 18 fingers examined
dicating imperfect resection;
When examined after three
showed an increase, but that
es, only 5 show any marked
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NS

cases after cervico-dorsal
y few cases after lumbar
gree. If all nerves to the
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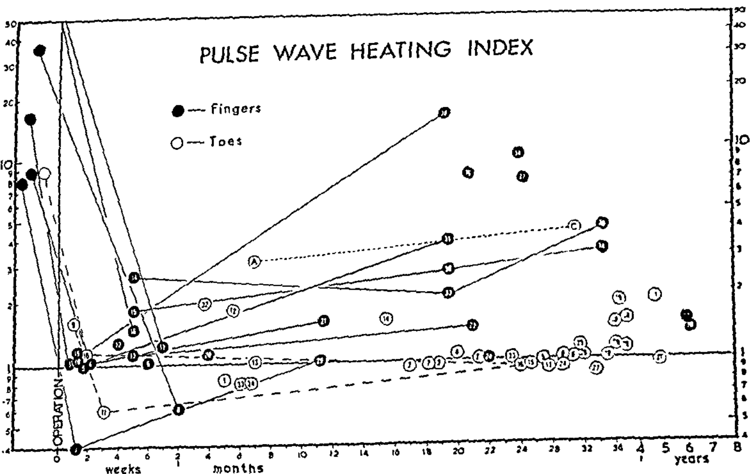
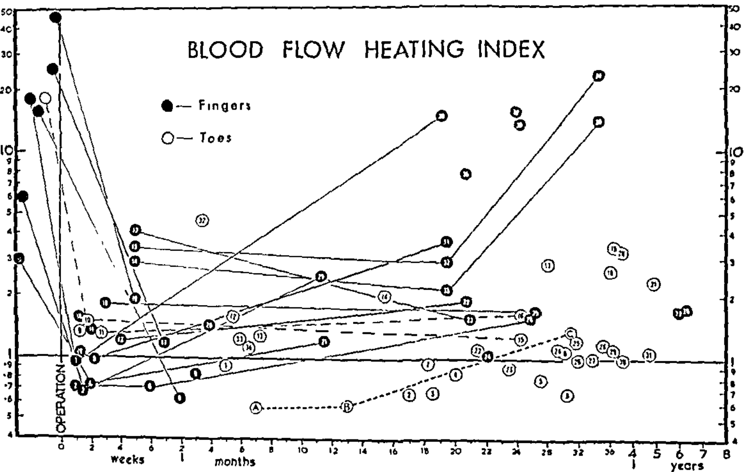

PULSE WAVE HEATING INDEX
Fingers
Toes
OPERATION
weeks
months
years

Fig. 70.



BLOOD FLOW HEATING INDEX
Fingers
Toes
OPERATION
weeks
months
years

FIG. 69.

all bunched closer to unity and, if anything, have a slightly more vertical displacement—indicating a greater increase of the flow index than that of the pulse wave. This, of course, was seen clearly in the comparisons between the two graphs (Figs. 69 and 70).

The conclusions from these two graphs are that there is little correlation between the blood flow and pulse wave indices in the toes, but that this correlation is better seen in the fingers, especially in cases where both are increased. These cases are those which show evidence of considerable vasomotor control. The two graphs would therefore support the general conclusion that vasomotor control does not recover in the toes, but is always present, or recovers to a considerable degree in the fingers.

The actual correlation between true blood flows and pulse waves is portrayed graphically in Fig. 62. The flows are expressed as ml. per 100 c.c. per minute as for 10 c.c. of digit. As explained earlier, the volume of the part is only an approximate figure, but since the pulse wave should truly be represented in proportion to the volume of the digit, the relationship of the two will be expressed diagonally.

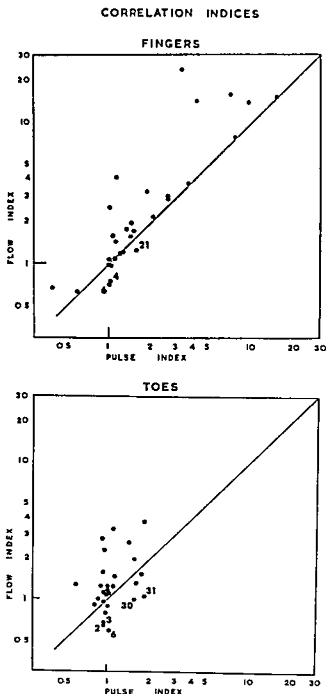


FIG. 71. Correlation of flow and pulse indices.

It will be seen that the correlation is better for fingers than it is for toes. Indeed, there are only four points for the fingers which lie above the diagonal line—two of these are from the same case and the other

Table X.—ANALYSIS OF VASOMOTOR RECOVERY

Blood flows	*Significant decrease*	*Significantly unchanged*	*Significant increase*	*Total*
FINGERS				
0–3 months . .	5	6	7	18
After 3 months .	0	3	18	21
Avulsion . .	*2*	*0*	*1*	*3*
TOES				
0–3 months . .	0	2	1	3
After 3 months .	5	12	12	29
Pulse wave	*Index* <0·8	*Index* 0·8–1·19	*Index* >1·2	
FINGERS				
0–3 months . .	2	7	5	14
After 3 months .	0	4	13	17
Avulsion . .	*0*	*0*	*2*	*2*
TOES				
0–3 months . .	*1*	*1*	*1*	3
After 3 months .	0	22	7	29

or more other cases in which severe peripheral vascular disease probably prevented the vessels from expanding after heating the patient. In the toes, however, only 7 cases showed an increase on heating out of 29, and in these it was much less marked than in the fingers. The remaining 22 cases on the toes showed no apparent change.

Simple measurement of the changes in the heights of the pulse wave would seem to offer a more convenient method of testing for the presence of vasomotor control.

The correlation between the blood flow and pulse wave indices is expressed graphically on a two-way logarithmic scale in Fig. 71 for the fingers, and for the toes separately.

A line is drawn on each of these graphs indicating equal degrees of increase. It will be observed that in the case of the fingers (upper graph) the majority of the points lie either along this line or above it and to the left. There are only 3 points, Nos. 6, 4 and 21, which lie to the right—indicating that the pulse wave index has increased more than that for the blood flow index. Two of these points are from the same finger, and the other is also from a case of Raynaud's disease with secondary peripheral vascular disease of the vessels.

The lower graph (Fig. 71) shows the points obtained from records of the toes. It will be evident that there is very little linear arrangement along a line showing equal increases in the two indices. The points are

two are also from cases showing severe peripheral vascular disease. For convenience in recognizing these points, those obtained before heating the patient are indicated by black centres, whereas those obtained after heating—which should show maximal vasodilatation—are indicated by hollow circles.

The correlation for true blood flows and pulse waves in the toes suggests that it follows a curve, as indicated by the interrupted line. This suggests that the pulse wave is proportionally larger than the blood flow except when the latter is very large or very small. These two graphs would not support the suggestion that the height of the pulse wave is always proportional to the blood flow in the digit. At least this does not apply to cases before or after sympathectomy for peripheral vascular disease or hypertension. It is possible that there may be a better relationship if the digital blood vessels were normal—but these patients rarely require sympathectomy. Only one such case (F.McC.) was examined here. This shows a very close relationship when most of the vasomotor innervation has returned. There is obviously considerable variation in other cases, many of which have abnormal vessels. When all cases are considered, although there is this large amount of individual variation, it is possible that in any one case at one time, during a heating test, the relationship may be better, as has been suggested by Melrose *et al.* (1954).

§2. DIGITAL VASOCONSTRICTION AFTER GENERAL BODY HEATING

In the discussion on the changes in the blood flow before and after heating the patient it will be recalled that some of the fingers and toes both showed a decrease instead of remaining unchanged—as would have been expected if vasomotor control had been removed. Statistical analysis (Table X) showed that 5 fingers, out of a total of 18 examined within three months of operation, showed this decrease, whereas 7 showed a significant increase. Similarly, 5 toes had shown a significant decrease out of a total of 29 when all cases were examined three months or more after operation. Twelve toes, examined three months to six years after operation, by this time had shown a significant increase.

Examination of the literature shows that this phenomenon had been observed previously under certain conditions. Wilkins, Doupe and Newman (1938) had found that the increase in blood flow in the fingers, resulting from local heating, is not so great as that produced by body warming. Earlier, Prinzmetal and Wilson (1936) had investigated the blood flow in the forearms before and after sympathectomy.

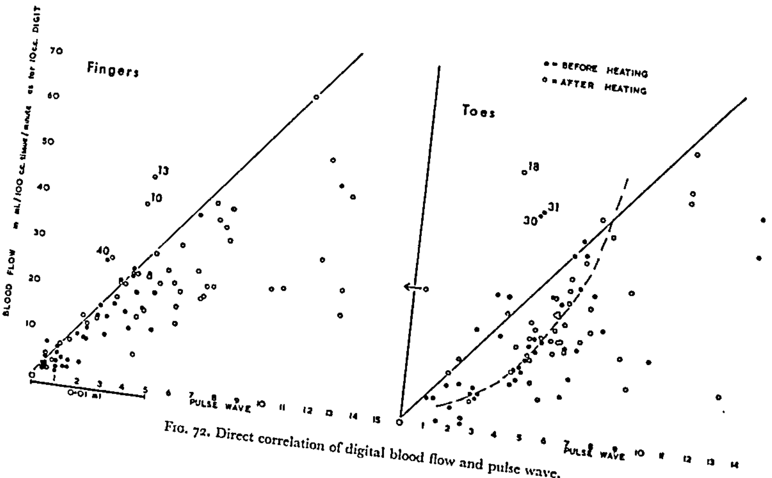


FIG. 72. Direct correlation of digital blood flow and pulse wave.

thought that the veins had definite vasoconstrictors, but that there was no evidence for vasodilators in them.

Further evidence of the existence of this phenomenon has more recently been given by Ahmad (1954) who kindly allowed the author to be present when these tests were performed. The patient had undergone a bilateral resection of T.2, T.3, T.4 and T.5 ganglia. Blood flow estimations were made on the hands, which were placed in water-controlled plethysmograph vessels, and body heating was induced by placing the patient's legs in water at 45° C. This produced no change in the rate of blood flow in either hand, indicating that vasomotor tone had been completely removed. When the temperature of the water around the hand on one side was raised to 41° C. (from 32° C.) and that around the other was cooled to 25° C., it was observed that there was a reduction of flow on the warmer side and an increase in flow on the cooler. When the temperatures of the hands were reversed, the now cooler hand had a greatly increased flow, and the now warmer hand showed a further reduction (*see Ahmad—figure 1*). These tests were confirmed on a subsequent occasion, but it appeared that the initial changes in the flows were not maintained and tended to revert to a less extreme level. Ahmad was able to find slight evidence of this phenomenon in two other cases, but neither showed it as well as in the case described above.

There has been confirmation of this phenomenon in animals. Ferguson and Levinson (1952 and 1953) perfused the isolated ear of the rabbit with oxygenated Locke's solution at different temperatures and found that the flow was decreased with a rise in temperature and vice versa. They drew attention to similar observations on the rabbit performed by Grant (1930), Grant, Bland and Camp (1932) and by van Dobben-Broekema and Dirken (1950*a* and *b*). Ferguson and Levinson suggested that in the isolated ear of the rabbit a decrease in the temperature of the perfusing liquid results in an alteration of the vascular pattern. They thought that the fluid may have been partially diverted from the capillaries through vessels of larger calibre, such as arterio-venous anastomoses. LeCompte (1941) measured the diameter of the arteries in a rabbit upon which he had performed a sympathectomy on one side. On heating the animal strongly he observed a slight constriction of the sympathectomized vessel, whereas the control on the opposite side continued to dilate (*see figure 1*).

In sympathectomized dogs, as reported by Ederstrom and Higginbotham (1952), vasoconstriction in response to hyperthermia was to be observed in the foot pad on the operated side and also on the normal side.

In the cases reported here this phenomenon of decrease in digital blood flows on heating the patient, appeared on 4 sides out of a total

In their first case, they found that ten days after an alcohol injection of the upper thoracic ganglia the blood flow was reduced from 1·1 to 0·75 c.c. per 100 c.c. per minute, on heating the patient's other arm. The same procedure carried out before operation had caused an increase in the flow from 0·65 to 1·75 c.c. per 100 c.c. per minute. In their second case, which was examined one month after a Smithwick type cervico-dorsal sympathectomy, the blood flow on the operated arm decreased on warming the patient from 1·2 to 0·75 c.c., whereas on the unoperated side it increased from 0·61 to 1·75 c.c. per 100 c.c. per minute. They explained this by a vasodilatation in the normally innervated areas causing diversion of blood from the sympathectomized segments, but this cannot be the case since the blood pressure on the two sides must be equal. Also, in the author's cases, there appears to be little alteration of blood pressure on heating the patients.

The opposite effect of cold on the forearm has recently been investigated by Clarke, Hellon and Lind (1958). They showed that it occurred over temperatures ranging 18°–1° C. both in normal and sympathectomized patients, though not in a case of brachial plexus lesion. They thought that the change of blood flow took place mostly in the muscle blood vessels and that it was mediated by sensory nerves.

Similar observations to those of Prinzmetal and Wilson have been made on the finger by Burton (1940). His experiments were carried out on two normal subjects who had been kept in a warm room for five days. If the legs of these subjects were subsequently heated so as to induce full vasodilatation, it was found that the blood flows in the finger decreased when compared with the rate of flow before heating. If, however, the patients were then kept in a cold environment, the reverse was the case—as is usual.

Wolff and Pochin (1949), when investigating the behaviour of single fingers in response to changes in local temperature, found that if one finger was immersed in cold water the subsequent vasodilatation on placing it in warm water again was much greater than on the control finger on the same hand. They considered that this phenomenon was the same as that described by Lewis (1930 and 1931). It was only seen, however, if the temperature of the water was cooler than 15° C. They confirmed that the 'Hunting reaction' was seen in the range 3° to 10° C. Stein, Harpuder and Ryer (1949), using a plethysmograph on the leg, found that sensitization of the blood vessels in the muscles, following sympathectomy, is more marked for the vasodilator than for the vasoconstrictor mechanism. They thought that sensitization of the cutaneous vessels is too inconsistent to be of significance. Carmichael (1950), however, had concluded that peripheral sympathetic fibres constrict the blood vessels on the arterial side of the vascular bed, but that there was also some evidence in support of vasodilator fibres. He

thought that the veins had definite vasoconstrictors, but that there was no evidence for vasodilators in them.

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In sympathectomized dogs, as reported by Ederstrom and Higginbotham (1952), vasoconstriction in response to hyperthermia was to be observed in the foot pad on the operated side and also on the normal side.

In the cases reported here this phenomenon of decrease in digital blood flows on heating the patient, appeared on 4 sides out of a total

of 10 sides which showed no evidence of vasomotor innervation shortly after cervico-dorsal sympathectomy, and in 5 toes out of a total of 19 toes which did not show evidence of vasomotor recovery after thoraco-lumbar sympathectomy. That is, it was found in 40 per cent. of fingers and 25 per cent. of toes after the appropriate sympathectomy—in the fingers of three patients and the toes of three others. The inadequate sympathectomy in the cases showing an increase in flow after body heating may have masked any decrease they might have shown.

It is interesting to note that in the only case in which postganglionic pathways were certainly absent—the case of brachial plexus avulsion examined seven and thirteen months after injury—this reduction of blood flow in the fingers, after general body heating, was seen particularly well (Fig. 66). It was no longer evident when sudomotor activity was apparent on the thumb—after thirty-one months. In no other fingers was the phenomenon seen after three months from the time of operation. All sensation was absent in the hand thirteen months after the brachial plexus lesion.

The explanation of this phenomenon still remains obscure. It has been suggested that, in the case of the fingers, the slight decrease in flow might have been due to slight cooling of the hand outside the cabinet during the course of the test. Although digital skin temperatures were not measured in any of the cases which showed the decrease in flow, in other cases which showed no change or an insignificant decrease in blood flow, the temperature of the fingers increased slightly (0·5°–1° C.) as the patient's own mouth temperature rose on general heating (Fig. 67—Case F.McC. Finger temperature 34·5° C. at start of body heating rose to 35·2° in forty minutes). In the case of the toes in which decrease of flow was measured when they were enclosed in the heating cabinet, it is almost certain that no decrease in local temperature could have occurred, but rather that they would have become warmed by the radiant heat rather more quickly than the fingers.

Should it be supposed that when a normal subject is cool the temperature of the arterial blood in the hands is not much below that of the body as a whole, reference should be made to some observations recorded by Bazett, Love, Newton, Eisenberg, Day and Forster (1948). Under such conditions cannulated thermocouples showed the temperature of the rectum was 36·9° C., that in the brachial artery 31·1° C. and in the radial artery only 21·5° C., without the subject being unduly cold. It is probable, therefore, that in the subjects showing this phenomenon of reduction of blood flow on heating the body, the temperature of the blood entering the fingers, even after sympathectomy, rose slightly during the course of the test.

Another suggestion is that this phenomenon might be due to adrenaline sensitivity of the vessels and that adrenaline is liberated under the

stress of prolonged body heating. Although this might account for the decrease in flow in the fingers, it is unlikely that it can explain that in the toes, for in all these cases in which it was seen, a splanchnic resection had been performed together with the sympathectomy and therefore the adrenals should have been denervated.

CONCLUSIONS

In the author's opinion the explanation is more likely to be due to the behaviour of denervated arterio-venous shunts, or even to the direct effect of temperature on the walls of the smaller blood vessels, particularly the arterioles. It should be pointed out that in the case of the fingers the blood flows were always initially small, due to either severe Raynaud's disease or general peripheral vascular disease. This, however, did not apply to the toes when relatively large blood flows were recorded before heating the patient. Grant (1930) has shown that the vessels of the rabbit's ear sometimes respond to local heating by constriction, and the same observations have been made by Clark and Clark (1934*a* and *b*) and summarized by Clark (1938). This paradoxical behaviour is reversible in any one arterio-venous anastomosis. That the over-all warming of a rabbit's ear causes a vasoconstriction has been shown in the normal rabbit by Ferguson and Levinson (1952 and 1953) and in the sympathectomized ear by van Dobben-Broekema and Derken (1950*b*) and LeCompte (1941). A similar phenomenon, the cold vasodilatation phenomenon, occurs principally at low temperatures. This was shown by Lewis (1930) to be a local reaction which he attributed to an axon reflex. Later workers, Greenfield and Shepherd (1950*a*), have shown that it still occurs, but to a lesser degree, when no nerves are present in the digit. The author suggests that the explanation may be due to the slightly increased temperature of the blood circulating in the finger after the patient has been heated. This would cause the majority of arterio-venous anastomoses or the arterioles to constrict slightly, with an apparent reduction in blood flow. It will be observed from the records illustrated that the capacity of the venous spaces decreased with reflex heating and that they offer a greater resistance to the flow in the arteriolar side of the arterio-venous anastomosis. This suggested explanation has not yet been proved, but experimental evidence on animals (cited above) has shown that it may occur. Recent observations by the author on the hamster cheek pouch which contains no arterio-venous anastomoses show that the arterioles particularly respond to local heat by constriction. When the cheek pouch is warmed, the arterioles begin to constrict at a temperature of about 36° C., and this constriction increases progressively up to 42° C. On cooling, again they will dilate along the same curve to about 36° C. but, for a few degrees below this temperature, the diameter of a vessel does not bear a

constant relationship to temperature and shows a lag in its response depending on whether the tissue is being warmed or cooled. At temperatures below about 15° C., vasodilatation appears and is very evident below 7° C. These changes are also seen in the veins which respond to heat by vasoconstriction, but the proportionate change in diameter is much less than that of the arterioles. The author intends to continue these experiments on transparent chambers inserted into the rabbit's ear with a view to direct examination of this problem in structures more closely resembling human digits.

Chapter 13

RECOVERY OF FUNCTION AFTER SYMPATHECTOMY

THE good results after lumbar sympathectomy, and the relatively unsatisfactory clinical and physiological results after cervico-dorsal sympathectomy, have been realized for many years. Sheehan had drawn attention to this contrast when reviewing the subject in 1933. Among the possible explanations that he considered was the postulate of Lewis (1929) that there was some special 'local fault' in the vessels of the fingers in cases of Raynaud's disease. Another possible factor was the suggestion that the vessels of the fingers showed a more powerful response to a local stimulus, such as cold. A third possibility was that of local vascular reflexes, which had first been suggested by Leriche, but Sheehan did not regard this as a satisfactory explanation. A fourth possibility was that of an extension of the periarterial sympathetic plexus along the main vessels of the limb. According to Langley, however, this does not extend into the hand, and this opinion has been confirmed by Stopford (1931). Sheehan believed that better results would be obtained if greater attention was paid to the more complete removal of the stellate and 2nd thoracic ganglia. Kuntz (1927) had earlier described an occasional ramus from the 2nd thoracic ganglion which joined the 1st thoracic nerve without passing through the stellate ganglion. This arrangement was relatively common, being present in about one-fifth of the dissections he examined. Later Kirgis and Kuntz (1942) described a less common but similar pathway from the third thoracic ganglion, which would also escape section if the stellate and second thoracic ganglia alone were excised.

Simmons and Sheehan carefully reviewed the whole subject in 1937, and examined a number of cases by testing for sweating on the hands and by skin temperature observations. By this time abnormal sensitivity to circulating adrenaline had been suggested as yet another possible cause for relapse after sympathectomy. Simmons and Sheehan, however, concluded that the cause of relapse after sympathectomy was not due to any 'local fault' or other special idiosyncrasy of the vessels of the hand, nor was it due to the influence of abnormal sensitivity to circulating adrenaline, though this could be demonstrated very shortly after operation. They found that the relapse coincided with the reappearance of vasoconstrictor fibres in the ulnar nerve, which could be blocked by

an injection of procaine at the elbow. They suggested, therefore, that regeneration of sympathetic fibres was the most likely reason for their reappearance.

It has been known for many years that sympathetic nerves are readily able to regenerate. Langley had carried out some experiments which demonstrated this in 1900, but it is interesting to consider that many of his results—especially early regeneration—could be better explained by the presence of intact intermediate sympathetic ganglia in relation to the nerve roots down to the level of the 4th lumbar nerve root. Langley had not realized that such ganglia existed, but they are now known to be present in the cat and other animals. Gaskell (1886—*page 15*) was apparently aware of their presence, but does not comment on their significance and they are not mentioned in his monograph of 1916 which was published posthumously. Langley had also shown that if the postganglionic cell itself was excised, preganglionic fibres were not able to establish a functional relationship with the peripheral end of the postganglionic fibres. His conclusions have more recently been confirmed by Hollingshead (1948). Lee (1929) has shown that sympathetic fibres in the cat had extraordinary powers of regeneration—a one-inch gap in the cervical sympathetic chain showed evidence of regeneration after 275 days, but if there was no gap, regeneration was apparent in twenty-six days and could be histologically verified. His conclusions have been confirmed by Butson (1950), who showed that sympathetic activity in the eye (rabbits and cats) could be regained when as few as four finely myelinated fibres could be seen in the peripheral portion of the previously sectioned cervical sympathetic chain. Many other workers have considered regeneration to be the most probable cause of recovery of sympathetic activity—Smithwick (1940*a* and *b*), Telford (1938), Haxton (1947*a* and *b*, 1948*a* and *b*, 1952 and 1954), Grimson and Durham (1949) and, in cats, Haimovici and Hodes (1940). No one has ever suggested, however, that if postganglionic nerve cells are excised they can be replaced by the body, nor that preganglionic fibres are able to establish connections directly with the blood vessels or sweat glands. It has always been presumed that regeneration, when it occurs, is either of a sectioned postganglionic fibre, or of a sectioned preganglionic fibre—in the latter event, the postganglionic cell may have been quite intact.

Felder, Simeone, Linton and Welch (1949) have reviewed a number of cases who had undergone sympathectomy for Raynaud's disease. They found that in cases examined six months to twenty years after operation vasomotor activity could be demonstrated in 60 per cent. and sudomotor activity in 61 per cent., but in the same cases combined it was only 48 per cent. In cases examined from six months to one year later, 25 per cent. showed vasomotor recovery and 20 per cent. sudomotor

recovery. Fairly similar figures have also been reported by Smithwick, Robertson and Farmer (1950). Simeone and Felder (1951) considered the result after ganglionectomy and 'preganglionic' resection, and concluded that it made very little difference which type of operation was performed. Learmonth (1950) believed that regeneration of the sympathetic might still be an important factor, but that the cells in the intermediate cervical sympathetic ganglia would provide an important alternative pathway. Robertson and Smithwick (1951) did not find the close correlation between physiological evidence of autonomic recovery and clinical results, as had been noted by Felder *et al.* (1949). Robertson and Smithwick did not observe vasomotor activity to be present in such a high proportion of cases, and presumably this was because they were using a less sensitive method. Felder *et al.* had suggested that the best form of sympathectomy was ganglionectomy plus root section, but Smithwick doubted whether this made much difference.

White, Smithwick and Simeone (1952), in an excellent monograph on the autonomic nervous system, have compared the physiological observations on cases after cervico-dorsal sympathectomy reported by Haxton (1947*a*), Felder *et al.* (1949) and Smithwick, Robertson and Farmer (1950). Haxton found evidence of autonomic recovery in all cases, and the others less frequently. This inconsistency would be better explained by the relative sensitivity of their tests. The results of clinical assessments were also given, but appear to be too subjective for comparison. White *et al.* (1952) concluded, however, that after lumbar sympathectomy regeneration may occur with the passage of time, but was more delayed in onset, less complete and less frequent.

Kinmonth and Hadfield (1952) also found that the results of ganglionectomy and 'preganglionic' resection were the same, and suggested, therefore, that nerve regeneration was not the chief cause of relapse. They believed that the possible causes of recovery of function might be adrenaline sensitivity, reorganization of alternative pathways and, possibly, the 'local fault' postulated by Lewis. The author will consider these and show that the first and third alternatives are no longer tenable.

Jepson (1951), also, did not believe that regeneration of the sympathetic expained the return of neurogenic activity in the upper limb. He re-explored a case which had relapsed two years after operation, and found that at the thoracic end of the sectioned chain a neuroma was present and that no anatomical connection between this and the somatic or sympathetic systems could be demonstrated. The neuroma, on histological examination, had confined its neurofibrils, and removal of the neuroma and an additional piece of thoracic chain failed to improve the patient's condition. He believed that the recovery of function after sympathectomy would best be explained by the compensatory

activity of alternative sympathetic pathways. He suggested that these might be through the intermediate cervical sympathetic ganglia; he thought that in the normal limb their activity was minimal and only as months passed did it become clinically significant.

Telford (1935) and Cohen (1953) have confirmed that on re-exploration of their cases they found no such regeneration of the sympathetic in the operative area. On the whole, Cohen thought it most likely that the explanation of such apparent regeneration was re-routing via the accessory sympathetic paths. Cohen has also commented on the decrease in blood flow immediately after sympathectomy. He stated the exact mechanism was unknown, but that it was generally ascribed to vasoconstrictive substances circulating in the blood. A later report has been that of Haxton (1954). In this Haxton still claimed that regeneration of divided fibres is the cause of relapse after sympathectomy. He based his conclusions on the results of his injection tests, but as will be described later, in the author's experience these have not been found to be conclusive.

In man, however, it does not appear that postganglionic fibres have any particular ability to regenerate at a greater rate than other types of fibres in peripheral nerve. Richter (1946), when he examined the sudomotor activity after peripheral nerve lesions, did not find any evidence to suggest this. Similarly, in the author's case E.C. (Chapter 5) it has been shown that sudomotor fibres regenerated after brachial plexus avulsion at a rather slower rate than did those for crude sensation. It should also be recalled that the patterns of anhidrosis after lumbar sympathectomy remain quite permanent, and there is no evidence that sudomotor fibres present in the second lumbar nerve on the front of the thigh (with ganglion cells in the intermediate ganglia) show any evidence of invading the nearby anhidrotic sacral dermatome on the back of the thigh. Indeed, this margin between a sweating and a non-sweating area is quite constant in position from year to year and does not appear to extend even one centimetre. It is therefore suggested that if ganglion cells, which ordinarily supply a certain dermatome, are resected, no other ganglion cells, which normally do not supply this dermatome, except possibly those from the next above or below, are able to re-innervate it even if the ganglion cells which normally innervate it are removed. This is so, even when both sets of ganglion cells remain intact in the body and only the preganglionic fibres which supply one set are sectioned. No autonomic activity will return to the skin in a dermatome which has been rendered anhidrotic due to resection of preganglionic fibres, unless these fibres regenerate or others near by are able to establish functional synapses (p. 91).

Ganglion cells remain in the lower lumbar and sacral sympathetic ganglia, but sympathetic activity does not return to these dermatomes.

Ganglion cells remain in relation to the nerves of the brachial plexus after stellate and T.2 ganglionectomy, but autonomic activity almost invariably returns to the upper limb. These ganglion cells in relation to the brachial plexus may be in a number of different sites. Firstly, they may be present in the middle, intermediate cervical and superior cervical ganglia, and along the cervical sympathetic chain. Secondly, they may be present in the intermediate sympathetic ganglia described in this region first by Wrete (1934*a*) and, in the adult, by Skoog (1947), and confirmed by Ehrlich and Alexander (1951). Illustrations from Skoog's paper are shown in Fig. 73, and indicate the frequency and complexity of the intermediate ganglia and their rami. Other sites of sympathetic ganglia are along the common, internal and external carotid arteries in the carotid plexi, and along the vertebral artery and also, possibly, in relation to other arteries in this region. Should preganglionic fibres re-establish functional connections with any of the ganglion cells in these regions, there would be every reason to expect autonomic activity to return to the upper limb. Such, indeed, must be the case. It has been realized that ganglion cells whose fibres supply the upper limb may be present in the sympathetic chain as low as the 3rd thoracic ganglion or lower (Goetz, 1948), and that ganglion cells supplying the lower limb may be present in the sympathetic chain from the 1st lumbar ganglion and extend into the sacral ganglia. After cervico-dorsal or lumbar sympathectomy, fibres which have been sectioned, but whose origin is from cells beyond that of the resection, may be able to regenerate across the block of scar tissue and pass down a nerve root to the periphery. Such fibres would be only few in number and have a long way to grow, so that if this is the explanation, then regeneration should occur only after a long interval after operation. Further evidence that the postganglionic fibres show little evidence of recovery is provided by the observation that when sudomotor activity returns to the upper limb it does so least along the ulnar border. This is contained principally within the first and second thoracic dermatomes and it is the sympathetic ganglia at these levels which have been resected.

If regeneration is the explanation for the recovery of function after sympathectomy, it must be due to regeneration of preganglionic fibres establishing functional connection with postganglionic cells. These cells have been left intact at the time of the original operation except that they have lost their original preganglionic supply.

As recovery of function does not occur after lumbar sympathectomy, the preganglionic fibres from the lower level of the thoraco-lumbar outflow cannot have been able to bridge the gap from the level, say, of the 1st lumbar sympathetic ganglion to that of the upper level of the sympathetic chain at, say, the 4th lumbar—i.e. two segments. Evidence

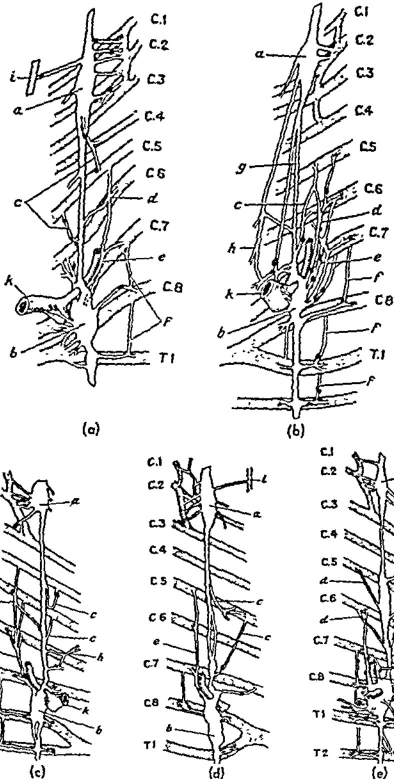


FIG. 73. To show position and connections of cervical intermediate sympathetic *ganglia in adults. Skoog, T. (1947). Lancet* Right *cervical sympathetic trunk and its* connections with spinal nerves in (a) and (b); left cervical sympathetic trunk and its connections with spinal nerves in (c), (d) and (e). Showing sympathetic ganglia marked in black: *a*, superior cervical ganglion; *b*, stellate ganglion; *c*, superficial communicating branch, *d*, deep communicating branch; *e*, vertebral nerve; *f*, rami communicantes grisei bipartiti of Wrete; *g*, sympathetic trunk; *h*, branch to plexus of carotid artery; *i*, vagus nerve; *k*, subclavian artery.

has been provided by Papez, Jansen and Dukes (1945) that in puppies, fibres from the 1st lumbar rami communicantes were often lost in connective tissue, and they became twisted into whorls as in a neuroma. A similar appearance is found in the rami from the 9th thoracic nerve root in the histological examination of the post mortem material (Case s.s.) described in Chapter 9.

Sympathectomy of the 2nd and 3rd lumbar paravertebral ganglia should include the lower level of the thoraco-lumbar outflow. Preganglionic fibres from these segments of the cord—usually L.2 but sometimes L.3—cannot regenerate to establish functional connections with the lower lumbar paravertebral ganglia nor with the lumbar intermediate ganglia at these levels. In the upper thoracic region, however, it is possible that some of the preganglionic fibres from the upper level of the thoraco-lumbar outflow may not have been sectioned at stellate and T.2 ganglionectomy, and might easily be able to establish functional connection with the ganglion cells in the region of the brachial plexus. It is possible that preganglionic fibres from the 1st and 2nd thoracic nerve roots may have been able to regenerate to establish functional connection with ganglion cells left intact after operation, but in the author's opinion the more likely explanation is that these preganglionic fibres were not all divided initially. It will therefore be necessary to examine more critically the possibility that the upper level of the thoraco-lumbar outflow of the sympathetic may have been left intact after a stellate ganglionectomy.

UPPER LEVEL OF PREGANGLIONIC OUTFLOW OF THE SYMPATHETIC NERVOUS SYSTEM

Experimental work on animals has suggested that the upper level of the thoraco-lumbar outflow is never above that of the 1st thoracic and usually only the 2nd or 3rd thoracic anterior roots. These observations originated from Langley (1892) who used the cat, dog and rabbit. Sheehan and Marrazzi (1941) and Sheehan and Pick (1943) have investigated this in the monkey, and Geohegan, Wolf, Aidar, Hare and Hinsey (1942) in the cat and monkey. Their conclusions are supported by the observations of Hinsey, Phillips and Hare (1939) that a stellate ganglionectomy was sufficient to produce permanent sympathectomy of the fore limb in the cat, though Kuntz, Alexander and Furcolo (1938) had suggested, on experimental histological grounds, that in the cat fibres from the 1st thoracic anterior root were able to synapse with ganglion cells in the inferior cervical ganglion, and that these cells sent axons which were distributed to the blood vessels and sweat glands of the fore paw.

In man, Foerster (1939) stimulated the nerve roots directly, but did not observe a vasoconstriction in those above the 4th thoracic anterior

root. Ray, Hinsey and Geohegan (1943) performed similar experiments in man, and observed the autonomic activity by the decrease in the electrical resistance on the fingers. Their results, and those of their co-workers at various times (Geohegan *et al.*, 1942 and Geohegan and Aidar 1942), have been summarized by Aidar (1947). The levels of the preganglionic outflow to the upper limbs were respectively—

cat .	. T.3–T.9
monkey	. T.4–T.10
man .	. T.2–T.10

though there was an occasional outflow from T.1 in man.

Netsky (1948) believed that it was usual for a small percentage of fibres supplying the upper limb to traverse the anterior root of the 1st thoracic nerve. He pointed out that Kuntz (1927), in dissections on the cadaver, had found similar evidence, and that Sheehan (1941) had found the 1st thoracic root to provide the upper level of the thoracolumbar outflow, and that in one of Sheehan's cases this was at the 8th cervical. Hyndman and Wolkin (1941) had thought that the preganglionic fibres to the upper limb were not present above the 2nd thoracic.

Sunderland (1948) and Sunderland and Bedbrook (1949) found that postganglionic fibres were present in all the roots of the brachial plexus in man and, in two cases out of four examined by Sunderland, preganglionic fibres were present as high as the 8th cervical nerve. Ray and Console (1949), when considering the sweating patterns on face and neck, believed that the preganglionic outflow must be above the 8th cervical anterior root. Further anatomical evidence has been provided by Pearson (1950), who found that in human embryos and foetuses white and grey rami communicantes could be recognized in relation to the 8th cervical nerve.

In later reports Ray (1953), although he does not give details of his experiments, found definite suggestions, from his records of skin resistance in the hand, that stimulation of the 7th and 8th cervical, and 1st thoracic roots would produce sympathetic responses. In 1955 Ray elaborated this statement by saying that he observed a prompt response in the hand on stimulating the 7th and 8th cervical roots in man even after the cervico-thoracic chain had been removed. It is possible that Ray was repeating in man the previous experiments of Geohegan and Aidar on the cat (1942, to be described later), and that these lower cervical nerve roots may ordinarily supply only the head and neck, but will supply the hand by a process of functional reorganization after the original preganglionic fibres to the hand have been severed.

Further experimental evidence is provided by Bridges and Yahr (1955), who observed vasoconstriction in the fingers on stimulating the anterior roots of the 8th cervical and the upper three thoracic nerves.

Similarly, Coldwater, Alexander, Cox and Randle (1957) found that when they stimulated the rami to the upper three thoracic ganglia, the 1st thoracic contributed significantly to the innervation of the sweat glands of the hand. They found no response when stimulating the chain below the level of the 4th thoracic ganglion. In one case on whom, eighteen months previously, they had already resected the first three thoracic ganglia without producing a Horner's syndrome, they stimulated the ramus from the 8th cervical nerve and observed vasoconstriction of the finger. Subsequent removal of the remainder of the inferior cervical ganglion produced a Horner's syndrome.

It appears, therefore, that there has been a growing realization that the 1st thoracic nerve root may not be the uppermost which contains preganglionic sympathetic fibres in man. Further evidence that this may be at the 8th cervical anterior root, or even above this level, is provided from the observations on Case C.A. (Fig. 25). In this case it was shown that after section of the anterior root of T.1, and confirmed degeneration of T.2 and T.3 nerve roots, autonomic activity was still present in the hand and was not abolished by a spinal anaesthetic which apparently reached at least to the level of T.4 (Chapter 5). Haxton (1947*a* and 1954) has described a technique whereby he is able to investigate relapses after sympathectomy. In this he claims that paravertebral injection of procaine, mixed with radio-opaque diodone may be injected at the level of the 2nd thoracic vertebra and will block the regenerated vasoconstrictor fibres to the hand. Haxton did not believe that the procaine injection affected the 1st thoracic or higher nerve roots or rami, since no Horner's syndrome was produced in cases which did not originally show it. The position of the diodone could be confirmed by X-ray. With Mr J. V. Crawford, of The London Hospital, the author has endeavoured to repeat these tests. Injections of procaine were also given at the lower cervical intervertebral foramina. The conclusions from these tests are that it is very difficult to be certain of the precise position of the injections, and that a preganglionic outflow in cases who have shown recovery after stellate and T.2 ganglionectomy is more likely to be from the 8th cervical rather than the 7th cervical nerve root. Injections at the 2nd thoracic level were likely to have spread upwards to affect rami from higher levels.

The conclusions are that after cervico-dorsal sympathectomy affecting stellate and 2nd thoracic ganglia some preganglionic fibres from higher levels remain intact.

FUNCTIONAL REORGANIZATION FOLLOWING PREGANGLIONIC FIBRE SECTION

Billingsley and Ranson (1918) found that for every preganglionic axon in the cervical sympathetic trunk of the cat there were thirty-two

cells in the superior cervical ganglion, though Wolf (1941) found a closer ratio. This does not mean that a preganglionic fibre synapses with only thirty-two postganglionic cells, since it is very probable that each ganglion cell has more than one preganglionic fibre effecting a functional synapse on it. Such a possibility, however, does not appear to have occurred to many workers on this question, but Hillarp (1946 and 1949) is definitely of the opinion that each postganglionic nerve cell is not innervated by one preganglionic neurone alone, but that several such neurones converge towards it. Apparently it was with this conception in mind that Geohegan *et al.* (1942) investigated the levels of origin of the preganglionic fibres in the cat, and determined, by direct stimulation, those nerve roots which carried the sympathetic pathway to the following structures. They found that

the eye received preganglionic fibres from spinal levels T.1–T.4 or T.5
the fore pad received preganglionic fibres from spinal levels T.3–T.9
the hind foot received preganglionic fibres from spinal levels T.11–L.3
the hair on the tail received preganglionic fibres from spinal levels T.13–L.3

It appeared that in the cat, whereas the uppermost level of the thoracolumbar outflow was the T.1 segment, the uppermost outflow of preganglionic fibres serving the fore pad was only T.3.

Geohegan and Aidar (1942) followed up these observations with a most interesting series of experiments. They performed laminectomies on cats and sectioned some anterior roots on one side only from T.3 to T.11. The changes in skin temperature were then measured and vasoconstrictor control was found to return on the operated side. After two to six months they re-exposed the nerve roots and measured the presence of autonomic activity in the fore pad by changes in the electrical skin resistance. They found that electrical stimulation of the anterior nerve roots produced positive responses from T.1 and T.2, and significantly large responses from T.3 nerve roots on the previously operated side. On the opposite side, however, no responses were obtained on stimulating at these levels, but only at T.4 anterior root or below—as had been found in the normals. From these observations Geohegan and Aidar concluded that a functional reorganization of preganglionic fibres must have taken place. Preganglionic fibres, normally only subserving the head and neck, must have given off collaterals to the postganglionic cells controlling sudomotor activity in the fore limb.

Evidence that this functional reorganization may also occur in man has been given by Ray, Hinsey and Geohegan (1943). They sectioned the anterior roots T.2–T.8 on each side in one patient, on whom they

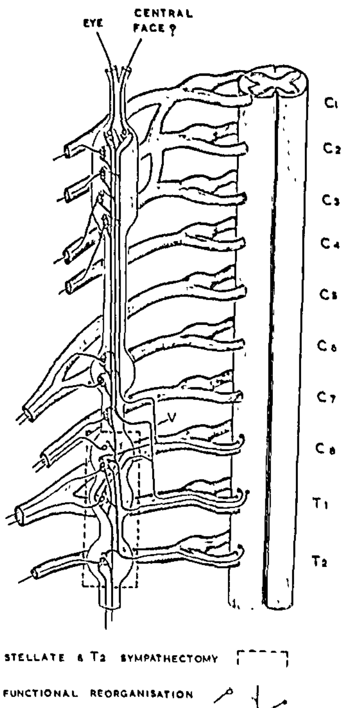


FIG. 74. To show sympathetic ganglion cells and pathways in cervical region. Suggested pathway via vertebral nerve V. A comparable aberrant pathway probably exists from the vagus trunk to the superior cervical and other ganglia in the head and neck.

had first determined the levels of the sudomotor pathways. These had included the T.9 anterior root on one side, but only as low as T.8 on the other. Within ten weeks of the operation, autonomic activity reappeared on the side which had shown a sudomotor outflow to the hand at the level of T.9.

Further evidence has been provided by the author's observations on cases of anterior rhizotomy of the lumbo-sacral anterior nerve roots. Although autonomic paralysis was evident in the feet shortly after operation, it very soon returned, and in the case examined six weeks after anterior rhizotomy, both sudomotor and vasomotor tone were almost the same as before operation. In these cases of anterior rhizotomy, intact preganglionic fibres from nerve roots above that of T.12 must have been able to establish functional connection with the ganglion cells supplying the lower leg.

In the author's opinion such a process occurs also in the cervicodorsal region after sympathectomy involving the stellate and T.2 ganglia. Preganglionic fibres may leave from the 1st thoracic nerve root, but all may not pass into the stellate ganglion before they synapse with postganglionic cells supplying the nerves of the brachial plexus. Other preganglionic fibres leave in the 8th cervical anterior root, and similarly will escape section by stellate ganglionectomy. There may even be a few fibres in the 7th cervical root. The pathways which these fibres may take are shown diagrammatically in Fig. 74. Other pathways may be via the carotid or vertebral arterial plexi as described in the human embryo by Kimmel (1955), or by the sinuvertebral nerve described by van Buskirk (1941). All these pathways are indicated in the diagram by —V. A comparable aberrant pathway to the central part of the face probably exists from the vagus (or even the glossopharyngeal) nerve to the superior cervical and other sympathetic ganglia in the head and neck. Autonomic nerve loops connecting the segmental nerve may also form an alternative pathway. These are illustrated in Skoog's figures: (see Fig. 73 (b) *f*, rami communicantes grisei bipartiti of Wrete). Since intermediate ganglia lie along the course of these loops, at least a part of them must contain preganglionic fibres. Such preganglionic pathways from the 8th cervical anterior root may not normally be concerned in the autonomic pathway to the upper limb, but only to the eye, head and neck. When the other preganglionic fibres from lower levels are divided by sympathectomy, the ganglion cells supplying the upper limb are at first without any preganglionic supply, and thermoregulatory sweating is no longer apparent. After a short interval of time, however, the intact preganglionic fibres—although they ordinarily supply only the head and neck—send off new collaterals to the ganglion cells supplying the upper limb. Since these preganglionic fibres have never been injured they do not 'regenerate'. The pro-

cess is, rather, one of 'functional reorganization'—the term used by Geohegan and Aidar (1942) and Monro (1954*a*) or collateral sprouting —a more apt description employed by Murray and Thompson (1956). It is possible that collaterals from these fibres to the ganglion cells subserving the upper limb may always have been present anatomically but are not physiologically active. This hypothesis would be most difficult to prove. Histological studies by Murray and Thompson (1957*a*) suggest that they do not occur in normal ganglia, but they are not precise on this point.

ADRENALINE SENSITIVITY

Meltzer and Meltzer (1903), Meltzer (1904) and Meltzer and Auer (1904*a* and *b*) were the first to describe the effects of adrenaline on blood vessels of the ear and on the eye, and its relation to sympathectomy. Elliott (1905), from further experiments, concluded that plain muscle when denervated shows an increase in the capacity for irritation by adrenaline which is greater than it had previously possessed. The imperfect quotation of his paper by later workers, and Elliott's own misquotations of Meltzer's and Auer's papers, has caused many years' confusion in the understanding of adrenaline sensitization. The reference Elliott gives to Meltzer's and Auer's work is not correct. Subsequently, Elliott states that in the ear vessels adrenaline sensitivity appears in sequence to simple decentralization by section of the preganglionic axons. For this statement he refers to Meltzer and Auer (1904*b*). In this earlier paper (*page 44*) they state that—

'for the blood vessels of the ear we have established that the simple section of the sympathetic is sufficient to prolong the constricting effect of adrenaline, and that the removal of the ganglion does not increase this effect.'

Freeman, Smithwick and White (1934) and Freeman (1935) described some experiments on man and rabbits in which they endeavoured to show that adrenaline sensitivity was greater after ganglionectomy than after 'preganglionic' section. They were aware of Elliott's paper (1905) and referred also to Meltzer and Auer, but it is evident that they could not have read the statement of the latter quoted above, or, if they did, they dismissed it. Following this, Smithwick designed a new type of operation in which he claimed that only preganglionic fibres to the upper limb would be divided. As has been shown here in the text (Case M.M.—Chapter 5), there is no reason to suppose that the isolated 2nd and 3rd thoracic sympathetic ganglia remain functional, and therefore the effects should be identical to those to be observed if these ganglia had been removed. White, Okelberry and Whitelaw (1936) demonstrated sensitivity of the blood vessels to adrenaline following sympathectomy, but Simmons and Sheehan (1937) showed that in

man this was only transient and could not be the principal cause for relapse after sympathectomy. Ascroft (1937), however, had shown in monkeys, by means of skin temperature observations, that adrenaline sensitivity might be an important factor in apparent vasoconstriction after cervico-dorsal ganglionectomy in these animals, and Simeone (1937), working on cats, confirmed that postganglionic denervation led to greater sensitization than preganglionic denervation. This increased sensitivity disappeared as the nerve supply regenerated. Many of the conclusions of the above workers were incorporated by Cannon (1939) into 'A Law of Denervation'. It should be noted, however, that Fatherree, Adson and Allen, writing in 1940, thought that the sensitivity to circulating adrenaline of the digital vessels in man was about equal after preganglionic or postganglionic section.

Kirgis and Reed (1949) appear to have been the first to question the value of 'preganglionic' sympathectomy. They investigated the effect of superior cervical ganglionectomy on the smooth muscle of the eye. After cervico-dorsal and second thoracic ganglionectomy in cats, there was evidence of re-innervation of autonomic fibres to the eye in three to six months, but there was no evidence of regeneration after superior cervical ganglionectomy. They therefore recommended that the latter procedure was more permanent.

Kirgis, Reed and Pearce (1950) reviewed a number of human cases which had undergone the two types of cervico-dorsal sympathectomy. They concluded that there was no proof that complete preganglionic section without regeneration was better than ganglionectomy. They found that ganglionectomy in their cases was always effective up to thirty months, but that preganglionic section was never effective after eight months, or only to a variable degree. They considered that efforts to remove as much as possible of the peripheral ganglia were most likely to be effective. They believed that sympathectomy would have been more popular if less attention had been paid to transient periods of enhanced activity of denervated smooth muscle in certain unphysiological conditions, and more recognition paid to regeneration from preganglionic fibres! Reed and Kirgis (1952) have summed up the question and concluded that hyperactivity of smooth muscle, which may follow interruption of preganglionic fibres, appears to be more significant than hyperactivity that depends on denervation.

CHANGES IN BLOOD FLOW IMMEDIATELY FOLLOWING SYMPATHECTOMY

Lewis and Landis (1930) appear to have been the first to observe that immediately after cervico-dorsal sympathectomy the hands were flushed and the digital arteries pulsated vigorously. By the second day the flushing had disappeared and these changes were no longer evident,

and by the fourth day pulsations could no longer be felt. Other observers have made similar observations. Johnson and Davis (1936 according to de Takats, 1937) found that following a cervico-dorsal ganglionectomy for Raynaud's disease the peripheral circulation returned to normal in less than three weeks. De Takats (1937) reached a similar conclusion, but thought it was due to improper selection of cases and suggested possible regeneration of the sympathetic. Schulenberg (1949) examined the vasomotor changes after peripheral nerve injuries. He found that the cutaneous area commonly passed through a warm phase of vasodilatation which continued for approximately twenty-one days, but after this the vessels entered a cold phase. This phenomenon has received much attention from Hoobler, Avera, Little, Peet and Bassett (1949) and from Barcroft and his co-workers (Barcroft and Hamilton, 1948*a* and *b*, Barcroft and Walker, 1949, Lynn and Barcroft, 1950, Walker, Lynn and Barcroft, 1950, and Barcroft and Swan, 1953). In their papers they described blood flow observations on the hand and foot performed before and on each day after sympathectomy. On the first and second day after operation the blood flow in the hand may reach a very high level (up to 50 ml. per 100 c.c. per minute), which is even greater than the maximal blood flow obtained on normal vessels after release of vasoconstrictor control produced by heating the patient's body. Towards the end of the first week this hyperaemia rapidly subsided, and after a fortnight the blood flow in the hand had returned to about the pre-operative level, although in the foot the residual flow remained about double after two to three months. They discussed the possible explanations for the regain of tone and, although they discounted the probability that this is due to circulating adrenaline, they believed that it might be due to an intrinsic change in the physiology of smooth muscular contraction. It does not appear that they had regarded the very high blood flows immediately after operation, and for the next day or two, as being anything beyond that which could be explained by simple removal of vasoconstrictor innervation. They were aware that this high level of post-operative blood flow was considerably greater even than in normal vessels, in which vasoconstrictor tone had been inhibited reflexly.

Similar observations have been made in the author's one case of sympathectomy with normal blood vessels (Case F.McC., Fig. 68). In this case the maximal blood flow after heating the patient was about 30 ml. per 100 c.c. per minute on the unoperated side, but seven days after operation on the other side the blood flow was almost 50 ml. per 100 c.c. per minute. Observations had also been made three days after operation and indicated an even faster rate of blood flow (not reported here). This fast level of blood flow after operation was not maintained. When nineteen months after operation vasoconstrictor innervation had

returned almost to the pre-operative level, the maximal blood flow after heating the patient was about 38 ml. per 100 c.c. per minute.

In the author's opinion the explanation of this phenomenon does not lie solely in the removal of vasoconstrictor control. The principal blood flow into the digits is through arterio-venous anastomoses. Although the changes of the calibre of these vessels are difficult to observe directly in man, they have been observed in the rabbit.

Grant and Pearson (1938) realized that arterio-venous anastomoses play a greater part in the regulation of blood temperature, and that in man and animals circulating adrenaline was not a factor responsible for the regain of vascular tone following sympathectomy.

Clark, Clark and Williams (1934) and Clark and Clark (1934*a* and *b*) made direct observations on newly formed and original arterio-venous anastomoses in transparent chambers inserted into the ears of rabbits. Their conclusions have been summarized by Clark (1938). He states that—

'stimuli which caused sudden increase in circulation followed by two or three days of increased blood flow may lead to the formation of numerous arterio-venous anastomoses in stable vascular networks. . . . Most of these new-formed arterio-venous anastomoses are temporary. With return of quiet circulation in the vascular area they diminish in size, lose some of their extraendothelial cells, and either become inconspicuous portions of the capillary network, or retract and disappear. . . . Some remain "permanent"—some of these are non-contractile, while others develop active contractility. The latter appear to be exactly the same as those with intact nerve supply and are under both central and local control. There is evidence that the acquisition of contractility is associated with regeneration of nerves. . . . Some permanent arterio-venous anastomoses were seen to grow small and disappear. Contributing factors were (*a*) lessening of blood flow; (*b*) formation of new capillaries supplied by the artery beyond the site of origin of the arterio-venous anastomosis; (*c*) persistent maintenance of a completely contracted condition in the arterio-venous anastomosis. Similar disappearance of arterioles has been observed associated with the same contributing factors.'

Such a description would seem to furnish a complete explanation for the changes in blood flow immediately following sympathectomy. The initial section of vasoconstrictor fibres serves as the stimulus which causes a sudden increase in the circulation. Although Clark's observations were made after injuries due to injection of methylene blue, and to local infection, there is no reason to suppose that sympathectomy should not produce a relatively similar picture. Sympathectomy has been performed on the rabbit, but this has usually been as an acute experiment in rabbits in which transparent chambers are inserted in

the ear. There does not appear to be any account of changes observed over several days after sympathectomy. The author has performed preliminary experiments on rabbits' ears in which transparent chambers have been inserted. The day-to-day changes in the blood flow have been made by direct observation. The picture is much the same as that described by Clark above. Many small vessels of veno-capillary type become much dilated. Some form true contractile arterio-venous anastomoses, but most of them begin to disappear after the fifth day following the superior cervical ganglionectomy.

In a transparent chamber the largest arteries are much smaller than those observed by LeCompte (1941) in the intact ear after sympathectomy. LeCompte found that when the animal was resting quietly the initial dilatation of an artery steadily decreased each day until the sixth, after which there was little further contraction. In the transparent chamber the smaller arteries do not seem to undergo such large changes in diameter, but the most striking feature after sympathectomy is the much greater velocity of the blood cells through them. LeCompte supported Grant (1930) in believing that the contraction of the artery was due to supersensitivity to an unknown hormone. Until the problem can be investigated more completely, this aspect of the return of 'tone' after sympathectomy must remain unexplained.

CONCLUSIONS

In the preceding chapters it has been shown that there are three areas in the body where sudomotor activity is retained after paravertebral sympathectomy, which, according to previous generally accepted ideas, ought to have abolished sweating. Firstly, it is retained in the lumbar region—in an escape area comprising at least the 1st and 2nd lumbar dermatomes—the reason for the retained activity here is the presence of lumbar intermediate sympathetic ganglia in close relation to the 1st and 2nd lumbar nerve roots. These are supplied by preganglionic fibres from the lowermost segments of the thoraco-lumbar outflow of the sympathetic. Secondly, sympathetic activity is retained in the perineal area corresponding to the 4th and 5th sacral dermatomes; and thirdly, it is retained in the central part of the face (central mask). The explanation for these last two areas has not been proved, but it is suggested that they are supplied by autonomic pathways leaving the brain stem or sacral cord through nerve roots which are not included in the generally accepted levels of the thoraco-lumbar outflow.

After lumbar sympathectomy it has been shown that the patterns of thermoregulatory anhidrosis remain permanently, and that vasomotor paralysis is also permanent except in a few cases (approximately 10 per cent.), when a slight degree of recovery appears after an interval of two or three years.

In the case of cervico-dorsal sympathectomy, however, it has been shown that whereas sudomotor paralysis may have been effected in most of the upper limbs, a certain degree of vasomotor control was still present in the about one-third of the cases examined shortly after operation. In the remaining two-thirds of those upper limbs, which were examined at intervals greater than three months after operation, sudomotor and vasomotor recovery had taken place in all cases (except one side which showed no vasomotor recovery). These conclusions on the invariable return of autonomic activity to the upper limbs show it

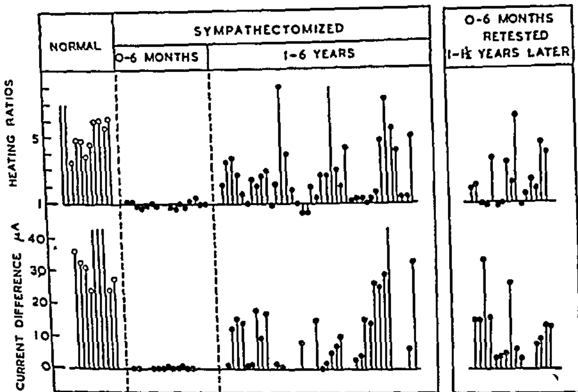


FIG. 75. Vasomotor and sudomotor activity in the hands. Barcroft, H., and Hamilton, G. T. C. (1948). *Lancet.*

to be rather greater than that found by some other workers, but they are confirmed by the observations of Haxton (1947*a*), who found evidence that physiological activity had returned in all of fifteen limbs examined one to fourteen years after stellate and T.2 ganglionectomy.

Barcroft and Hamilton (1948*a* and *b*) have investigated the evidence of vasomotor and sudomotor activity in sympathectomized hands. In cases examined within six months of operation they found no evidence of the presence of either, but in other cases examined one to six years after operation either vasomotor or sudomotor activity was invariably present, and usually evidence of both could be obtained. Their findings are illustrated in Fig. 75 (courtesy of Professor Barcroft). Of those cases originally examined within six months of operation, almost all showed

evidence of having regained some degree of autonomic innervation when examined again twelve to eighteen months later.

In the author's opinion the return of autonomic activity depends not so much on the time interval since operation but rather on the sensitivity of the method by which it is detected. It is probable that if cases examined by other workers—e.g. Simmons and Sheehan (1937 and 1939)—which did not show evidence of any return of autonomic activity at one year but did show it at five years, had been examined with a more sensitive method, they would have revealed a slight degree of autonomic activity even at six months or earlier. No attempt, therefore, has been made to try to determine the time at which autonomic function returns to the upper limb after sympathectomy, except to observe that vasomotor recovery was present in every case examined (except for one side) after a post-operative interval of three months. Possibly, examination of all patients at regular monthly intervals after operation might furnish more information on this aspect, but this would be very tedious for the patients and for a single observer. The number of cases examined after cervico-dorsal sympathectomy is smaller than those examined after lumbar sympathectomy, but since the former had all shown evidence of return of autonomic activity at the time of their last examination, whereas the greater majority of the latter had not, there would have been no particular advantage in extending the number of cases examined after cervico-dorsal sympathectomy.

It is concluded that reorganization of preganglionic fibres by collateral sprouting offers a better explanation for recovery of function after sympathectomy. Regeneration of both preganglionic and postganglionic fibres may be a contributing factor, but it is likely to account for the cases which show evidence of recovery of function only after a long interval—two years or so, after sympathectomy.

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* Newcombe *et al.* (1959) have provided a very recent objective analysis of a large series of hypertensive patients treated by operation. They found a survival rate of 76 per cent. for five years which was in accord with the published figures of surgical cases and in favourable contrast with any series of patients treated conservatively. (Newcombe, C. P., Shucksmith, H. S., and Suffern, W. S. (1959). 'Sympathectomy for hypertension. Follow-up of 212 patients.' *Brit. med. J.* i, 142-144).

Chapter 14

§1. CLINICAL APPLICATIONS

Although operations for sympathectomy are not at present being performed so frequently as they were a few years ago, there have been a number of recent reports suggesting that this method of treatment, when employed on carefully selected cases, is still superior to all others. Thus Wells (1956), in reviewing 150 cases of thoraco-lumbar sympathectomy for hypertension, which he had followed up for five years, concluded that the swing away from surgery had been too complete, since it had much to offer the patient in the relief of distressing symptoms, conservation of vision and prolongation of life.

Similar support has been provided by Longland and Gibb (1954), who showed that a group of hypertensive patients with more severe retinal changes were particularly benefited by operation as opposed to medical treatment. These conclusions contradict the earlier opinions of Platt and Stanbury (1950). Other more recent reports have been reviewed in two leading articles in the medical press (*Brit. med. J.*, *1955*, ii, 893–894, and *Lancet*, 1956, ii, 1031–1032) and both have added a plea that operation for hypertension should be employed more frequently in selected cases.* Surgery will certainly continue to have a place in treatment until pharmacology can offer an ideal and universal alternative. Zintel, Sellers, Jeffers, Mackie, Hafkenschiel and Lindauer (1955), while endorsing the better results of surgical as compared with medical treatment, suggest that the latter may be more effective after sympathectomy. In all these reports, although the authors usually describe the types of operations to which their patients were subjected, no attempt has been made to correlate the extent and manner of thoraco-lumbar sympathectomy with the clinical response of the patient. Similarly, there has been, in these reports at least, no assessment of anatomical denervation. It would have been a great advantage to know if the planned extent of the operations had been achieved in all cases.

Haimovici (1951), in an editorial on the criteria for sympathetic denervation, stressed that this must be complete to be successful. He noted the variations of the normal anatomy of the paravertebral sympathetic chain and the rami communicantes, and also considered the part which the intermediate ganglia might play in the presence of residual sympathetic pathways. He suggested that vasomotor responses

would provide an indication of the degree of sympathetic neurectomy, but he realized they would be inadequate and non-specific for the area of denervation. The segmental levels could be estimated more accurately by studies in the changes in the areas of sweat secretion. These would indicate the denervated dermatomes.

The foregoing chapters will provide a basis for assessment of the completeness or otherwise of paravertebral sympathetic resection over varied segments. These segmental areas of denervation may be correlated with the intended levels of resection for each individual patient. Unfortunately, it has not been practicable to extend these observations to the assessment of clinical change in the diseases or the symptoms for which these patients originally underwent their operations. To do so would have introduced a greater subjective element from the observer than the more objective records of vasomotor and sudomotor innervation reported here. It would also have made this monograph much longer; nevertheless reports of this nature are needed. Perhaps a team of surgeons, physicians, physiologists and anatomists will be able to provide such a comprehensive study.

Haimovici has suggested that the presence of autonomic denervation in splanchnic and skeletal muscle can be estimated from the skin patterns. The position of the intermediate ganglia may invalidate this assumption. In Chapter 9 it has been seen that, in the upper lumbar region, the cells in the intermediate ganglia lying on the grey rami communicantes were more likely to retain intact connections to the skin, whereas at the same segmental level, those in the ganglia on the white rami showed evidence that their fibres to the viscera had been divided. On the other hand, at these levels, there were still small bundles of fibres, running with the lumbar vessels which connected the intermediate ganglia with the mesenteric ganglion tissue lying in front and at the sides of the aorta. These bundles were very small and it would seem unlikely that they would furnish a very effective pathway for sympathetic impulses to the viscera. In this respect, however, it must be remembered that, certainly in the cervical region, even a few preganglionic fibres and their collateral sprouts can produce a great deal of autonomic recovery of function.

Objective evidence on this point may be deduced from the absence in men of the power of ejaculation. Loss of this power is very often associated with the resection of the first lumbar ganglion. Although there are various reports that this disability may disappear, it is interesting to recall that it did so in one patient (Case W.S.—page 40) at the same time as thermoregulatory sweating was observed to return to part of the T.11 dermatome on one side.

Various reports have claimed that the results of lumbar sympathectomy for peripheral vascular disease are improved if the 1st lumbar

ganglion is also resected. Since there may be as many ganglion cells in the intermediate ganglia associated with this nerve trunk as there are in the corresponding paravertebral ganglion, it is difficult to understand what benefit can ensue. It has been pointed out by Ross (1954), however, that this ganglion should also be removed if there is an iliac arterial block and it is desired to dilate the collateral vessels in the hip region. For more distal vascular disease of the legs, Hohf, Dye, Olwin and Julian (1954) have shown that paravertebral sympathectomy T.12–L.3 offers no advantage over the standard operation L.2–L.3. Ray (1955) agrees with this opinion. Ordinarily for peripheral vascular disease, in men, the first lumbar ganglion should be preserved.

Although bilateral thoraco-lumbar sympathectomy is always followed by marked postural hypotension, this does not usually persist for long. The blood pressure eventually returns to its pre-operative level in all but one-fifth of the patients. It will be most interesting to discover if this is associated with more adequate visceral autonomic denervation and whether any particular type of operation is more likely to achieve it. In this respect it seems unlikely that any advantage is to be gained by extending the resection more cranially. The incision should be placed so as to enable the surgeon to make a very thorough dissection of the sympathetic chain and the splanchnics as they pass through the diaphragm and its crus, and he should also resect the lumbar splanchnics and the upper part of the lumbar paravertebral chain to below the level of the thoraco-lumbar outflow. Attention has already been drawn to the better vasomotor results of the retro-pleural as opposed to the transthoracic operation.

In regard to the autonomic denervation of skeletal muscle, evidence is even more lacking. Intermediate ganglia usually supply the skin over the inner side of the calf, though the underlying muscles are supplied from lower segments. In the forearm it has already been shown that some degree of vasomotor innervation almost invariably has returned when tested three months after operation. Although there are many reports of observations in the calf on blood flow after sympathectomy, the general finding is that in many cases of peripheral vascular disease of the legs there is little permanent change (e.g. Shepherd, 1950). This may well be due to the small extent of permanent denervation: any subjective clinical improvement may be due solely to section of visceral afferents.

As an indication of what can be achieved by careful observation of digital blood flow before and after lumbar sympathectomy, Husni and Simeone (1957), by means of body heating tests, showed that they could predict the clinical effect of the operation in 73 per cent. of cases with intermittent claudication. Even then, half the patients in whom a poor response in blood flow was predicted still improved with sympathec-

tomy. Although such studies are the most likely to provide information on the best form of treatment, whether by operation or not, they will be of even more value if they can be correlated with the segmental pattern of autonomic denervation. Similarly, both Mavor (1955) and Edwards and Crane (1956) agree that the clinical condition, with prior assessment of the degree and site of arterial obstruction, must be carefully considered before selecting patients for lumbar sympathectomy. Such criteria would be even more valuable were it known that in any particular patient a sympathectomy or other neurectomy would denervate the vessels down to a specified level.

An example discussed in Chapter 5 is that of Case W.T. in whom the unusually low extent of the 'escape' area into the L.4 dermatome prevented the healing of an ulcer above the medial malleolus, whereas a similar ulcer above the lateral malleolus had healed. This was surrounded by skin that was anhidrotic, and presumably had also lost its vasomotor innervation.

Local anaesthetic block, even when given at precise levels, may give misleading information as to the anatomical denervation to be achieved by a paravertebral sympathectomy at the same levels—especially in the upper lumbar segments. This is because the intermediate ganglia related to the rami communicantes and nerve trunk are involved in the area of diffusion of the local anaesthetic whereas they are left intact after operative sympathectomy. Case R.R. (page 60) shows the area of anhidrosis after local procaine injection within the psoas muscle sheath at the levels L.2, L.3 and L.4. Obviously the area of autonomic denervation is much more extensive than that found after paravertebral sympathetic resection at comparable levels. As Husni and Simeone (1957) have shown, there may be an indication that a certain type of sympathectomy will benefit the clinical condition even if such an operation is not practicable.

'Chemical sympathectomy' with injections of alcohol or phenol as suggested by Haxton (1949) should, in theory, produce an area of autonomic denervation closely approximating that of procaine injection. Unfortunately, it seems that it is very difficult to be sure of the precise location of the tip of the needle (White, Smithwick and Simeone, 1952—*pages 462–464*) and, although this method has been taken up by several other workers, there are no reports of the dermatome patterns of denervation or correlation with the levels of injection. The limited observations of Boyd and Monro (1949) and on Case S.W. reported here (page 104) suggest that the method may produce patchy areas of anhidrosis and that these are only transient.

In the cervico-dorsal region, local injections of anaesthetic solution (or of sclerosing chemicals) may produce interference with sympathetic function, which is very different from the later effects of a ganglion-

ectomy in the same region. In this case the discrepancy is probably not because of the intermediate ganglia, which also occur in this region, but is due to other sympathetic pathways, alternative to the cervical sympathetic chain. These may be paralysed by an injection of local anaesthetic, especially if this is of large volume, but are not interrupted by the operation. In the upper dorsal region 'chemical sympathectomy' appears to be very successful in abolishing the pain of angina pectoris. Attempts have been made to define the site of the anaesthetic solution by prior injection of radio-opaque oil, but the latter does not diffuse as readily as the aqueous solution, and the area involved by the anaesthetic may be much more extensive. Presumably an aqueous solution of phenol would behave in a similar fashion.

There is another aspect of 'chemical sympathectomy' which does not yet appear to have been tried. At operation it should be possible to inject the connective tissue around the rami communicantes with small quantities of sclerosing solution under direct vision. The injection should be aimed towards the nerve root with the intention of affecting the intermediate ganglia (Figs. 40 and 41). The paravertebral ganglia would then be resected as before. If this were done at the upper lumbar levels, the whole of the lower limb should be rendered anhidrotic. In the region of the stellate ganglion, local injection of sclerosing solutions could be made under direct vision into the region of the vertebral nerve, and at other sites where preganglionic fibres from the 1st thoracic and 8th cervical nerves might be passing towards the intermediate and other cervical ganglia. Skoog's diagrams (Fig. 73) may provide a guide to their site and the pathways involved. Care would have to be taken to avoid injury to blood vessels and seepage of the sclerosing solution back into the wound. The results should achieve a much greater degree of sympathetic denervation, even if they were not permanent. An added advantage over anterior rhizotomy, which might otherwise be considered for severe cases, is that the sclerosing solution, if injected near a nerve root, is likely to have a greater effect on the fine autonomic fibres than on the much more heavily myelinated fibres to voluntary muscle.

Although good results in cases of hypertension and peripheral vascular disease are only to be expected if the sympathectomy is complete for the region concerned, interruption of all sudomotor pathways is not required for hyperhidrosis of the hands and feet. In the case of the hands it has been shown that after cervico-dorsal sympathectomy, a varying degree of sudomotor activity almost invariably returns. This minimal sweating, which is so much less than the distressing amounts which caused the patient to seek operation, is sufficient to keep the hands moist enough to provide a grip of smooth objects. After lumbar sympathectomy the resultant anhidrosis may be too perfect. The feet are dry

and scaly, and ladies complain that they too frequently ladder their stockings! Ross (1954) was struck by the seeming anomaly that sympathectomy produced good results for hyperhidrosis of the hands but not for Raynaud's disease. It is evident that for the former condition the 'imperfect' operation is better for the patient. Lumbar sympathectomy appears to achieve excellent results for Raynaud's phenomenon in the feet.

A successful sympathectomy in one region may precipitate or aggravate symptoms in another region. Thus thoraco-lumbar sympathectomy for hypertension may induce Raynaud's phenomenon in the hands as well as unpleasantly increased sweating on the arms and upper chest. Similarly, cervico-dorsal sympathectomy for hyperhidrosis of the hands may be followed by such exacerbation of the condition in the feet that another sympathectomy may be requested. If a lumbar sympathectomy is performed, the patient is now distressed by drenching sweat on the trunk.

It would appear, therefore, that some lesser operation might be more satisfactory, and in this respect 'chemical sympathectomy' might suffice. For hyperhidrosis of the hands it would seem that the inferior cervical and 1st thoracic ganglia should not be included in the ganglionectomy.

For facial and gustatory hyperhidrosis the problem is not so simple. If sympathectomy is to be performed, it would be illogical to do less than remove the inferior cervical ganglion, and in some cases a superior cervical ganglionectomy might be preferable. It should be recalled that gustatory sweating not uncommonly develops after cervico-dorsal sympathectomy (Haxton, 1948*a* and *b*). Section of the auriculotemporal nerve appears to be adequate for the auriculotemporal syndrome. For other forms of facial hyperhidrosis it would seem best to perform preliminary diagnostic anaesthetic block and to abolish sweating in the desired area with the minimal volume of anaesthetic solution.

For this condition, and for peripheral vascular disease of the hands, it may be impossible to avoid the production of a Horner's syndrome. As has been stressed by Ray (1953), the cervico-dorsal sympathectomy should not be restricted on this account. Ray suggests that if a symmetrical appearance is essential, a superior cervical ganglionectomy may be performed on the opposite side. A better alternative, if this is needed, would be to perform a plastic operation on the upper eyelid by shortening the tendon of the levator palpebrae superioris muscle. This should not be done too soon, or over-correction may result when the Horner's syndrome begins to recover. Such an operation was performed on Case C.A., with apparently excellent results at the time. Patients are usually unaware of any inequality in their own pupils.

Other indications for sympathectomy have been discussed by Lear-

month (1950). He points out that such operations may also be performed to interrupt visceral sensory pathways. For angina pectoris he recommends resection of the upper four thoracic ganglia on the left side rather than their injection with alcohol. Sympathectomy may also relieve other visceral, renal and causalgic pain. Indeed, after thoraco-lumbar sympathectomy, as has been pointed out by Wells (1956), a patient may develop an acute abdominal emergency which remains 'silent' and causes him no distress. This freedom from visceral pain does not apply to the scar of the wound. Transient intercostal neuralgia may be very distressing after rib resection in these patients, but it does not usually persist for long.

There are innumerable accounts in the literature of sympathectomies of various types for many varied conditions. One striking feature common to them all is the complete absence of any objective post-operative study of the influence of autonomic denervation on the original condition. Until such reports are available, no comment is possible.

§2. RECOMMENDATIONS

In all patients the extent and the method of the operation will have to be considered in relation to the nature of the disease and its severity. The most complete operations are required for peripheral vascular disease and hypertension. On this basis the following recommendations can be made.

CERVICO-DORSAL SYMPATHECTOMY

Resection should include as much ganglion tissue as possible, and an attempt should be made to resect the middle and intermediate cervical ganglia supplying rami to the brachial plexus. This operation has already been suggested by Ray (1953). The resection should extend at least as low as the 2nd thoracic ganglion, but there is no evidence that the 3rd need be removed, though perhaps this should be done if easily accessible. It should be realized that not all preganglionic fibres will be divided, and there would seem to be little advantage in performing intradural section of the 2nd and 3rd thoracic nerve roots if the 1st thoracic and 8th cervical are left intact.

In severe cases of Raynaud's disease or after its relapse following a previous sympathectomy, consideration should be given to the possibility of sectioning the 1st thoracic anterior root, but this should be done *only* after prior electrical stimulation of the relevant roots and observation of the voluntary muscle and autonomic responses.

Alternatively, sclerosing solutions such as phenol might be injected in small quantities under direct vision at the time of ganglionic resec-

tion. This should be done with a view to blocking the alternative sympathetic pathways in this region. If results appear to be sufficiently encouraging, the procedure might be extended to include less severe cases.

THORACO-LUMBAR SYMPATHECTOMY

The retro-pleural operation would appear to be more satisfactory than the transthoracic approach. There seems to be no advantage in extending the operation above about the 8th thoracic level unless it is desired to relieve symptoms of angina pectoris. The rationale of 'preganglionic' section to include the roots of the greater splanchnic nerve appears to be mistaken. Great care should be taken to remove completely the splanchnic nerves and the sympathetic chain as they pass through the diaphragm and its crus. The sympathetic chain should be removed as low as the lower border of the 3rd lumbar vertebra. Metal clips should be placed at the upper and lower ends of the intact chain so that these levels can be localized by X-ray examination.

On the analogy that if any preganglionic fibres persist intact it is better to remove as many ganglion cells as possible, it might be expected that the coeliac ganglion should also be resected. There is no evidence at present that this conveys any advantage: even if it were removed, there is a great deal of other para-aortic and pre-aortic ganglion tissue which would be less accessible. Recent reports in the literature suggest that partial adrenalectomy should not be attempted.

Under certain conditions where it may be necessary for sympathectomy in the lumbar region to be as complete as possible, it may be advisable to inject the rami communicantes of the upper three lumbar nerves with a sclerosing solution such as phenol. This should be done under direct vision with a view to the involvement of the intermediate ganglia associated with these nerve trunks. The alternative would be to section the anterior roots of these nerves, but this would cause herniation of the lower abdominal wall.

LUMBAR SYMPATHECTOMY

All that is ordinarily required is resection of the paravertebral sympathetic chain from the level of the upper border of the 2nd to the level of the lower border of the 3rd lumbar vertebra.

Finally, may a plea be made for adequate anatomical follow-up on all patients after all types of sympathectomy. Only when the intended levels of resection at operation, the observed area of sudomotor denervation and the degree of vasomotor paralysis can all be correlated with the change in the clinical condition will it be possible to say what treat-

ment is best for the patient. It may be operative, or not, or a combination of operation with medical treatment.

It is hoped that the studies reported here will enable surgeons and all others interested in the autonomic nervous system in man to gain an understanding of what changes in the function of this system are likely to result from any particular operative procedure. These recorded observations should also indicate the changes in function that may occur with the progress of time.

Chapter 15

GENERAL SUMMARY

PART ONE

¶ THE patterns of thermoregulatory sweating have been determined on 26 cases after thoraco-lumbar sympathectomy, 12 cases after lumbar sympathectomy and 12 cases after cervico-dorsal sympathectomy—the last two groups include 6 cases upon which four-quarter sympathectomy had been performed.

¶ Most of these cases were examined on repeated occasions at varying intervals after operation, and the changes, if any, in the sweating patterns have been discussed.

¶ The patterns of sweating produced by an injection of carbachol into some of the patients are compared with the thermoregulatory sweating patterns in the same patients.

¶ The presence or absence of vasomotor control in either the fingers or the toes has been investigated at the same time as the sweating tests. Maximal inhibition of vasoconstrictor control was produced by heating the patient in a hot-air cabinet.

¶ After the appropriate extent of paravertebral sympathectomy it has been found that sympathetic activity is constantly retained in the following areas:

(*a*) An escape area comprising the 1st and 2nd lumbar (and usually the 3rd lumbar) dermatomes, with an occasional extension upwards into the 12th thoracic dermatome or higher, after thoraco-lumbar sympathectomy; (*b*) an area in the perineum comprising the 4th and 5th sacral dermatomes, after lumbar or thoraco-lumbar sympathectomy; (*c*) an area in the central part of the face (central mask) which may have associated with it an area over the larynx, and others around *the external auditory meati, after cervico-dorsal sympathectomy.*

¶ These findings on the sweating patterns, vasomotor innervation and autonomic activity in the eye, face and neck are summarized in

Table I for Thoraco-lumbar sympathectomies,
Table II for Lumbar sympathectomies,
Table III for Cervico-dorsal sympathectomies.

These Tables I–III include data on the presence or absence of sympathetic activity (*a*) within three months of operation; (*b*) after three months from the date of operation.

¶ It has been found that after lumbar or thoraco-lumbar sympathectomy, sudomotor activity, if initially absent, did not recover within four years of operation (in one case it has not recovered after twelve years). In these cases slight vasomotor recovery became apparent in 30 per cent. of the feet examined after an interval of two to three years.

After cervico-dorsal sympathectomy, sudomotor activity was usually absent in the hand if the sympathectomy included the 2nd thoracic ganglion, but in all cases sudomotor activity had recovered, at least partially, when examined three months or more after operation. Vasomotor activity in the hand and sympathetic activity in the orbit showed similar recovery after an interval three months or more after operation.

Evidence from sweating patterns would suggest that the lower level of the thoraco-lumbar outflow of the sympathetic is at least as low as L.3 in 30 per cent. of cases.

¶ Transthoracic thoraco-lumbar sympathectomy does not usually produce as complete a resection of sympathetic pathways as does the retro-pleural operation.

¶ Cases upon whom section of the anterior roots of certain nerves had been performed have shown that autonomic activity recovers very quickly after section of the preganglionic fibres ordinarily supplying a limb, provided that other preganglionic fibres have remained intact. It is suggested that this process of functional reorganization is by collateral sprouting from intact preganglionic fibres.

¶ One case of traumatic brachial plexus avulsion has provided evidence that autonomic postganglionic fibres regenerate at a slightly slower rate than sensory fibres. Sudomotor and vasomotor activity in the hand showed no evidence of recovery until two and a half years after the injury.

¶ Notes on aspects of pilo-erector activity are made in the text. Local pilo-erector activity is retained after appropriate sympathetic ganglionectomy, but is absent if there is an accompanying lesion of sensory nerves.

PART TWO

¶ Lumbar intermediate sympathetic ganglia constantly exist on the 1st and 2nd lumbar nerve roots, and are thus able to furnish the postganglionic cell stations to the 1st and 2nd (and probably 3rd) lumbar dermatomes in which the sweating persists.

¶ The existing pattern obtained on one case has been correlated with the post-mortem findings and an exact agreement found between the levels of the lumbar intermediate ganglia present and the dermatomes in which sweating persisted.

¶ Eighteen lumbar intermediate sympathetic ganglia were found on one side and twenty on the other side of the case examined *post mortem*.

Approximately 6,500 cells were present in the intermediate ganglia in relation to the 1st lumbar nerve root. This compares with approximately the same number of cells in the 1st lumbar paravertebral ganglion on the opposite side.

¶ The position of these intermediate ganglia is variable. They are found in both 'grey' and 'white' rami communicantes, and also on, in and around the upper four lumbar nerve roots on each side. Their positions, size and connections are summarized in Tables IV and V.

¶ Besides the normal 'grey' and 'white' rami, other autonomic pathways may exist: (*a*) as fine nerves along the lumbar arteries, towards the ganglion cells on the sides of the aorta in the lumbar regions—this pathway is not interrupted by ordinary paravertebral sympathectomy; (*b*) as occasional fine nerve loops between one nerve root and another. Each of these pathways may be associated with 'intermediate' ganglia at one or both ends.

¶ Evidence is produced that the 'intermediate' ganglia in relation to the 'white' rami communicantes mostly supply the viscera, whereas those in relation to the 'grey' rami or on the anterior primary division of the nerve root mostly supply the somatic areas.

¶ Doubt is expressed whether either 'grey' or 'white' rami communicantes in the upper lumbar region can be considered as containing only preganglionic or only postganglionic fibres.

¶ The findings in regard to the numbers of the lumbar intermediate sympathetic ganglia have been confirmed in human embryos and foetuses.

¶ The calibre spectra of the anterior roots of spinal nerves and of the cranial nerves in man are reproduced in Tables VI, VII and VIII by kind permission of Professor Rexed.

¶ Suggestions are made that the explanation of sweating retained in the perineum after lumbar sympathectomy is from sudomotor pathways leaving the sacral cord in the 4th sacral anterior root which is below the lowermost level of the thoraco-lumbar outflow.

¶ Similarly, it is suggested that an alternative preganglionic sympathetic pathway may exist by way of fibres leaving the brain stem via certain cranial nerves (VII, IX or X). The developmental fate of the epibranchial placodes associated with these nerves (and the 5th cranial nerve) is considered in relation to the areas of skin of the face and neck where sweating activity is retained after cervico-dorsal sympathectomy.

¶ The phenomenon of gustatory sweating is discussed.

PART THREE

¶ Vasomotor effects are discussed and summarized in Table IX, which also indicates the results of observations made on the same digit

at varying intervals after sympathectomy. The figures obtained at each observation are examined statistically and expressed as an index.

¶ Vasomotor activity was retained in the hand in almost 50 per cent. of sides examined immediately after operation, and showed recovery in all other cases when examined three months or more after operation.

It is shown that in the fingers, vasomotor control had recovered in every case examined more than three months after operation. (In one case, which showed sudomotor recovery in both hands at two years, vasomotor activity remained absent on one side only.)

In the toes, vasomotor activity is absent in most cases, but two to three years after operation, about 30 per cent. of the feet examined showed slight recovery. The results are shown in Table X.

¶ The observations obtained by measuring blood flows are compared with measurements on the height of the pulse wave. It is concluded that the latter may be a more convenient method for determining the presence or absence of vasomotor innervation.

¶ The correlation between the increase in blood flow and increase in pulse wave is not constant. There is less correlation in the toes than in the fingers, but in the latter it becomes relatively constant only in cases which have recovered much vasomotor control.

¶ Of those cases not showing some degree of recovery of vasomotor control, about 20 per cent. of fingers and 35 per cent. of toes showed a statistically significant decrease in blood flow after heating the patient. The possible explanations for this are discussed.

¶ Explanations are offered for the very large blood flows immediately after sympathectomy and for their reduction over the next few days, but there seems to be no adequate explanation for the decrease in calibre of the larger arterioles. [In a preliminary communication Burn and Road have recently suggested that supersensitivity of blood vessels following denervation is due to the loss of their noradrenaline content. It would seem probable that this loss is associated with the change in vascular tone. Burn, J. H., and Rand, M. J. (1958). The cause of the supersensitivity of organs after degeneration of sympathetic nerves. *Lancet*, ii, 1213.]

¶ The literature in regard to explanations for the recovery of function after sympathectomy is reviewed.

¶ It is concluded that functional reorganization of preganglionic fibres by collateral sprouting offers a better explanation for recovery of function than does regeneration—though the latter may occur in certain cases after an interval of two to three years.

¶ In the cervico-dorsal region it seems probable that these sprouts come from preganglionic fibres leaving the cord in the 1st thoracic or 8th cervical nerve roots (or possibly even higher). These pathways

will not be sectioned by ordinary cervico-dorsal sympathectomy.

¶ In the lumbar region a resection of the 2nd and 3rd lumbar ganglia will interrupt the lower level of the thoraco-lumbar outflow of the sympathetic. Collateral sprouting of preganglionic fibres to ganglia caudal to these levels ordinarily does not occur.

¶ Recent reports suggest that sympathectomy for hypertension may be the best form of treatment in selected cases and that it may improve the results of medical therapy.

¶ For hyperhidrosis of the limbs, a less complete sympathectomy may produce a more satisfactory effect on symptoms than a more radical operation such as is required for peripheral vascular disease.

¶ Sclerosing chemical solutions when injected along the course of rami communicantes under direct vision at operation might improve the results both cervico-dorsal and lumbar sympathectomies if clinical conditions require this.

¶ Recommendations are made for different types of sympathectomy. It is pleaded that all patients should be examined for residual autonomic activity after operation.

Appendix

CLINICAL APPARATUS

SWEATING TEST CABINET*

This cabinet is constructed of *Holoplast*, which is a commercial type of plastic double cavity material 1 in. thick. It is designed to be made up from three standard 8 ft. × 4 ft. sheets of this material with the minimum of waste. It is white coated on both sides and requires no painting: it can be worked with ordinary woodworking tools.

The cabinet (Fig. 76) measures 6 ft. 3 in. long × 3 ft. 4 in. wide and 3 ft. 5 in. high, and is thus designed to fit over the mattress and rest on both ends of the frame of an ordinary hospital bed. It consists essentially of a roof compartment measuring 9 in. deep which contains thirty-four vertical radiant-heat bulbs (316 c.p., 30 W., 230 V.) and above which is a curved aluminium reflector. The roof compartment is supported at each end by two hinged flaps. The flap at the head end is strengthened by vertical battens at each side to which the hinges are secured, and by 'elbow' pattern folding brackets. At the foot end, the two vertical battens to which hinges and 'elbow' brackets are also attached are secured to a foot piece 12 in. high which extends about 4 in. above the edge of the mattress. The upper part of this flap is fitted with a detachable end section similar to the side sections. The two end flaps may be folded inwards for convenience in storage, and will then protect the electric bulbs.

From the side edges of the roof compartment the side sections are suspended by means of half-hinges, which will allow one or both side sections on each side to be slid off for easy access. The foot end section is fitted with similar hinges. The side sections measure 4 ft. and 2 ft. in length respectively × 2 ft. 8 in. high, and are fitted with rubber seals to make a relatively airtight joint with the head and foot flaps. Perspex windows are fitted at each end and in each of the side sections; the latter's windows may be slid upwards for access. Side ports at the level of the arms are also fitted in the two headward side sections. This allows the forearms to be placed outside the cabinet for physiological observations on blood flow, etc.

As an alternative arrangement the two side sections at the foot end may be removed and the foot end section suspended from a cross-partition in the roof compartment 2 ft. from the foot end. This allows the patient's legs to project outside the shortened cabinet beneath the transposed foot end section for physiological observations on the feet, etc. (Fig. 77).

The cabinet is fitted with electrical switches to provide different heating power, and a distance-reading air thermometer. No particular provision is made for ventilation, as in practice the patient receives sufficient air through the space between the sides of the mattress and the side sections.

With a patient inside and with all the heat bulbs on, the air temperature rises from 20° C. to about 45° C. in half an hour. This is the normal time required to raise the patient's mouth temperature from 98·4° F. to 99·6° F.

When examining a patient for the sweating test, all but the bulbs at the foot end are switched off. The examiner, after removing his coat, tie, collar, etc., ducks under

*The cabinet was designed by the author and constructed in the Works Department of The London Hospital.

one of the side sections and arranges a blanket to screen the space beside him between the side section and edge of the mattress, so that sweating will not be inhibited by the cool air from outside the cabinet. Measurements are made on the patient's skin in the relevant areas, but those not being immediately examined are kept covered with a blanket.

Should the expense of constructing such a cabinet deter anyone from attempting to verify the area of sudomotor denervation, the combination of electric blankets and ordinary blankets may provide a more accessible alternative. The patient should be examined in a small warm room free from draughts. Though a cabinet is more convenient for research purposes, it is quite possible to determine the margin between sweating and non-sweating skin with simpler heating apparatus.

THE AUTHOR'S PLETHYSMOGRAPHIC APPARATUS

PRINCIPLES

This apparatus will record from both limbs simultaneously. The plethysmograph cups are of two shapes, to fit either fingers or toes, and are made of Perspex. Standard cups will fit the majority of patients, but smaller ones are available. The cups are sealed to the digit by 'rubber grease', which does not melt as easily as does Vaseline when the fingers become warm. Fig. 78 shows a plethysmograph cup and venous occlusion cuff attached to the great toe of a patient. The volume of digit enclosed is not critical, since only changes in flow and pulse wave are measured and expressed as an index. More care is taken to place the seal at the proximal inter-phalangeal joint of the finger or the terminal joint of the toe. In a number of cases the volume of the digit enclosed has been measured and found to be about 10 ml. If the toes are very large, not so much tissue is included in the cups. Rubber pressure cuffs are placed above the base of the finger or toe, and these may be inflated to a pressure—usually 70 mm.Hg.—from an air reservoir.

The Perspex cups are connected to horizontal glass tubes containing a short column of alcohol. The connections are made by flexible polythene tubing of about 3-mm. bore and about 3 ft. in length, which is the minimum to allow of recordings to be taken from both hands when these are extended through either side of the heating cabinet.

Light from the horizontal filament of an ordinary household clear lamp passes through a condenser onto the two glass tubes in turn, since they are parallel and in almost the same optical plane.

The meniscus at one or other end of an alcohol column refracts the light and appears opaque, whereas the alcohol columns act as cylindrical lenses. The images of each tube are projected, after reflection by a right-angled prism, onto photographic paper by means of an anastigmat lens. The volume of air in each tube may be adjusted by a syringe connected to a three-way tap. The meniscus will be displaced by any change in the volume of air in the system, without any change in pressure. The images of the menisci are focused on the photographic paper, so that a displacement of 0·01 c.c. is equivalent to 5 mm. on the paper and 0·5 mm. may easily be read, which corresponds to 1 c.mm displacement. The optical condenser may be rotated about a horizontal axis so as to produce a slight raising or lowering of the plane of the optical axis. By this means the alcohol columns, acting as cylindrical lenses, are slightly displaced one to another, and will therefore produce images of different density on the slit in the plate over the recording paper. At the start of each recording, a characteristic mark is made with the calibrating syringe to indicate the right-hand side. By this means it is always possible to distinguish the menisci in the two tubes and therefore to distinguish the records from each side, even though the meniscus at one

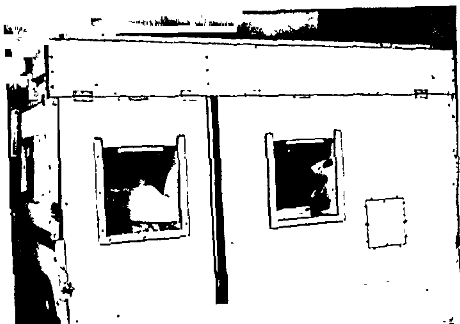


FIG. 76. Sweating test cabinet.

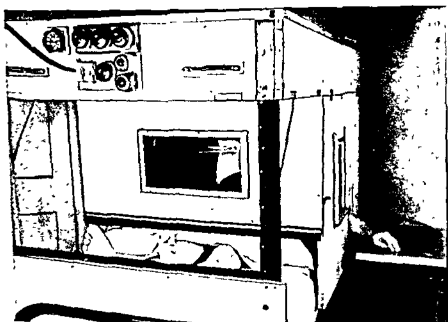


FIG. 77. Sweating test cabinet arranged for plethysmography of fingers or toes.

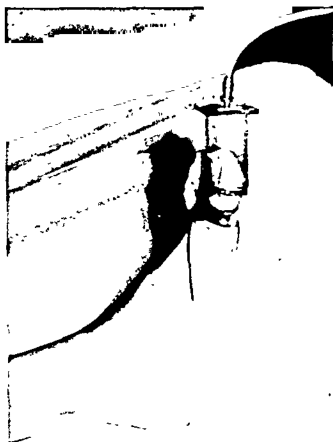


Fig. 78. Toe in plethysmograph cup.

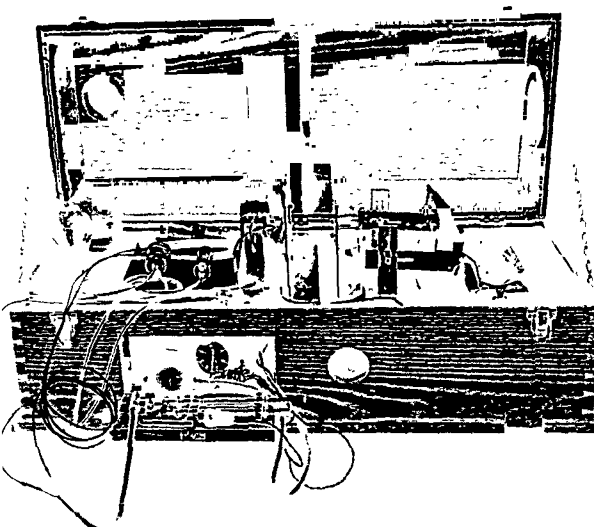


Fig. 79. Digital plethysmograph. Toe and finger cups are shown.

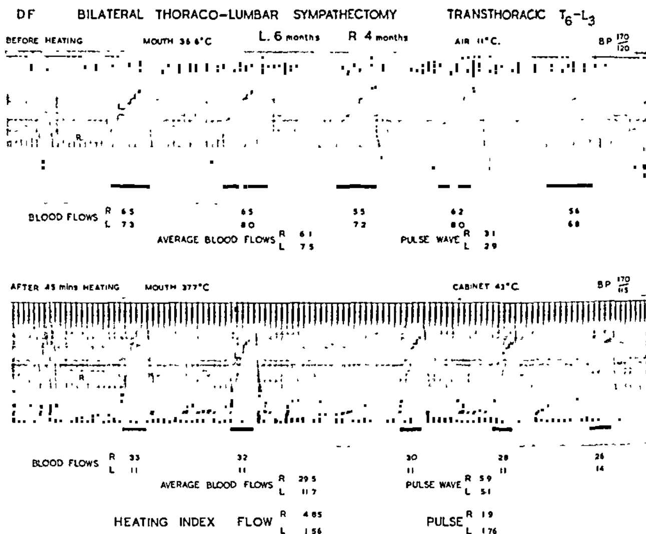


FIG. 80. Specimen plethysmographic record.

end of an alcohol column may pass out of range, and that at the other end of the same column come into range, at the other end of the slit. The length of the slit is 12·5 cm. and, since it may be effectively doubled in this way, the total range is 25 cm., corresponding to a displacement of 0·5 c.c., and this may be read to an over-all accuracy of 0·001 c.c. As one tube is necessarily nearer to the limb, it has a larger bore to correct for the parallax error. Calibrations have shown that the over-all accuracy is within 5 per cent., which is quite sufficient for clinical experimental work. In the centre of the paper, where most of the observations are recorded, the accuracy is much better than this. The photographic paper is 5½ in. wide ex-government soft-grade waterproof bromide, and only about 4½ in. is used for the actual recording; the margin may be used for notes and for the record of a signal marker. A ruled graticule is placed beneath the slit so that 5-mm. markings are made on the record. The whole apparatus is enclosed in a light-tight box, fitted with a mirror in the roof, by which the movements of the alcohol columns may be observed—side by side at right angles to the optical axis. This enables the observer to gain an idea of the changes in volume of the fingers as they are recorded. A dark-sleeve is fitted so that pencil notes may be made directly on the paper during recording (Fig. 79). The bromide paper is developed in ordinary bromide developer, diluted 1:4, contained in a long-length film-developing tank.

When the occlusion cuffs are inflated to a pressure just below diastolic blood pressure, the slope of the peaks of the pulse waves will indicate the rate of blood flow. This may be most conveniently measured by means of a transparent scale which can be adjusted for the speed of paper (Figs. 80 and 81). The initial rise when the venous occlusion cuff is inflated is ignored, but the slope of the peaks of the pulse waves is measured over the next three or four pulse beats. At slow flows this may usually be quite easily determined, but at fast flows, when the venous spaces are filled with only two or three pulse beats, it is more difficult to place the nylon filament of the transparent scale satisfactorily over the peaks of three pulse waves in line. It is therefore less practicable to measure fast rates of flow with accuracy, and it seems probable that, on the whole, these are given too low a value. When calculating the rate of flow, usually at least five observations are made before heating the patient, and five more after heating the patient. It is an advantage, when calculating the statistics of the figures obtained to have a total of six observations on each occasion. Usually this is done by taking an extra observation at a faster speed, so that the height of the pulse wave may be more easily measured. This frequently shows a dicrotic notch or even two such pressure waves.

CONSTRUCTION AND METHOD OF USING TRANSPARENT SCALE FOR READING PLETHYSMOGRAPH RECORDS

CONSTRUCTION

Transparent acrylic sheet (Perspex ⅛ in. thick) measuring 30 × 17 cm. is large enough to keep the record flat, though only the middle 20 cm. is engraved on the underside. On the left-hand edge is a recessed slot in which slides a brass (or plastic) slide to which is attached a nylon thread. This is inserted through two holes with a groove between them on the under surface and secured by a knot on the upper surface. The slide may be clamped by a knurled screw-button so that the point of attachment of the nylon thread may be set at the level indicated and corresponding to the speed of the paper—here shown in Fig. 81 as 9·5 seconds per 5 cm. of record. The figure 10 on this scale is 10 cm. from the top edge and the range of setting is 3·5–16 seconds per 5 cm. of record corresponding to 1·25–0·3 cm./sec.

Along the top edge is a reciprocal scale reading to the left and indicating blood flow as ml. per 100 c.c. part per minute expressed as for a 10 c.c. part. Along the top edge,

at a distance 10 cm. to the right from the centre line of the slide, is inscribed point '6'. The nylon thread will cut this point when it lies at an angle of 45° to the line of movement of the record and when the slide is set for 10 seconds per 5 cm. of record (0·5 cm./sec.).

This figure corresponds to the calculated displacement of the alcohol column and *optical magnification onto the record of this particular plethysmograph* where 0·01 c.c. is equivalent to 5 mm. For any other plethysmograph new calculations will have to be made to determine the figure to be cut by the thread when it lies at 45°.

Similarly, the point '3' lies 20 cm. to the right of the centre line of the slide. It represents the lowest value of blood flow which can be read when the speed of the

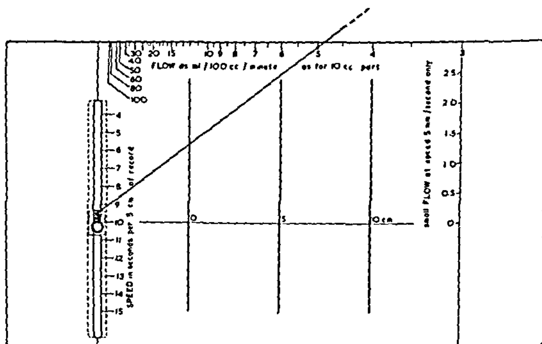


Fig. 81. Transparent scale for reading plethysmograph records directly in blood flow per 100 c.c. of digit. The slide may be set and clamped in position corresponding to the speed of the record. A nylon thread is aligned over the image of the meniscus *in each tube.*

record is other than 10 seconds per 5 cm. (0·5 cm./sec.). In Fig. 81 the nylon thread is shown as indicating a flow of 4·9 ml./100 c.c./minute for a 10 c.c. part.

On the right side, extending vertically below the point '3', is a scale for measuring small flows. The zero on this scale is at the level of the slide setting for 10 seconds per 5 cm. record, at which speed only is it accurate. If a small flow is to be read at any other speed, the scale is moved vertically up or down on the record by the distance over which the speed scale is different from 10 seconds per 5 cm. The nylon thread is kept over the same point on the record and the reading is made of the new point it now cuts on the right-hand scale.

One horizontal line and 3 vertical lines at 5 cm. intervals enable the scale to be aligned correctly on the record. The vertical lines 5 cm. apart are used for counting the number of 1 per second time marks on the record. This number is used for setting the slide.

METHOD OF USE

In use, the slide is set and the scale brought in turn into a convenient position for measuring the slope of each flow on the record. The alignment is checked and the

nylon thread laid over the peaks of the first three or four pulsations after the venous occlusion cuff has been applied. These should lie on a straight line and the initial jump is disregarded. Should the nylon thread not cover the peaks, the scale is moved to right or left until it does so: a reading is made of the figure cut by the thread, and this may be written on the lower edge of the record.

ANALYSIS OF RECORDS

Fig. 80 shows specimen records obtained six months after transthoracic thoraco-lumbar sympathectomy (Case D.F.). On the top record are the five readings taken before heating the patient, and on the bottom are five more taken after heating the patient for forty-five minutes, after which the mouth temperature had risen to 37·7° C. On the upper record it will be noticed that there is a considerable jump in the record on both sides when the pressure cuffs are inflated (indicated by the signal marker on the edge of the record). Time marks are in seconds. The pulse wave is about 3 mm. on each side, and the slopes of the increase in volume of the toe due to the rate of blood flow are satisfactorily straight. The blood flow at each observation is not identical, but the average is about 6·1 on the right and 7·5 on the left—expressed as ml. blood per 100 c.c. of toe per minute. On testing again after heating the patient, it may be noticed that the height of the pulse wave is much increased, being rather greater on the right than on the left (5·9 and 5·1 mm.); and that the blood flows are also increased, being greater on the right than on the left. It will be seen on this record that there is considerable advantage in reading the meniscus at both ends of the alcohol column—when the image of the meniscus goes off at the top, the meniscus at the other end of the alcohol column comes in at the bottom (seen well in the second observation). The average blood flows on this occasion were—

(right) 29·5; (left) 11·7.

From these may be calculated—

Heating index. Flow (right) 4·85.
(left) 1·56.
Pulse (right) 1·9.
(left) 1·76.

The blood pressure is relatively unchanged, there being only a drop of 5 mm. in the diastolic pressure after heating. These records indicate incomplete sympathetic resection, especially on the right side.

CONSTRUCTION OF DIGITAL PLETHYSMOGRAPH

The instrument is designed to record on 5½-in. wide ex-government waterproof bromide paper (soft or medium grade). A schematic diagram of the plan and elevation is shown to scale in Fig. 82. Light from the horizontal filament (*F*) of a clear glass 200-V., 100-W. lamp (over-run at 230 V. to provide greater actinic brilliance) passes through a double plano-convex condenser (*C*) of 6·4-cm. (2½-in.) diameter, which is held in an adjustable mount so that it can be raised or lowered slightly and also rotated about a horizontal axis. The light from the filament is thus condensed on to an anastigmat lens (*L*). In this instrument the focal length is 5·5 cm. (2⅛ in.) and aperture *f* 3 5. It is held in a bracket whose position can be adjusted and also acts as a screen to prevent extraneous light from the lamp reaching the photographic paper. (See also Fig. 79).

With small springs two glass tubes *A* and *B* are held horizontally beside each other by two small horizontal Perspex plates clamped to another bracket whose position is also adjustable in a vertical direction. Between the brackets is another screen fitted to the lid, but in which part is cut away to allow light to pass to the lens. The tubes contain a short column of clear alcohol (*Al.*) (about 3 cm. long—not critical), and may be filled by means of the calibration syringes from a reservoir of alcohol into which their open ends (flexible) may be dipped.

Tube A, bore 2·8 mm.—*37·5 mm. displacement of meniscus* = 0·25 ml.

Tube B, bore 2·86 mm.—36·0 mm. displacement of meniscus = 0·25 ml.

Unequal bores allow for correction of the parallax error. The glass wall of each tube *is 1 mm. thick.*

The meniscus at either end of the alcohol column may be recorded on the photographic paper, thus effectively doubling the maximum displacement.

[illegible]

axis of the rays of light passing through each in turn may be slightly displaced by

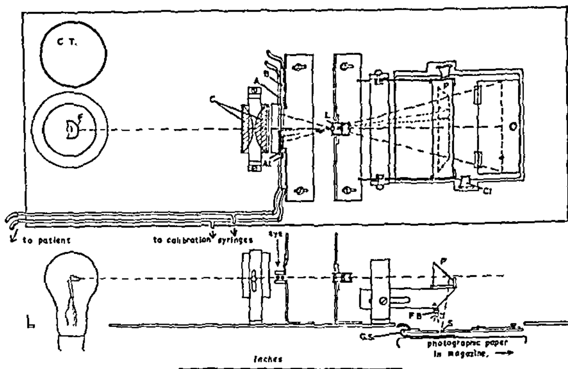


FIG. 82. Plan and elevation of digital plethysmograph.

rotating the condenser about its horizontal axis. In this way, the intensity of the light from each alcohol column forms an image of different density on the slit, and the menisci from the two tubes may thus be always distinguished.

With the lens and tubes used in this instrument, the following measurements are given, but these would need alteration if a lens of slightly different focal length were employed.

Filament to condenser .	. 26·7 cm. (10½ in.)
Filament to tube B .	. 30·8 cm. (12¼ in.)
Tube B to focal point of lens .	7·15 cm. (2¾ in.)
Focal point of lens to slit	. 22·85 cm (9 in.)

A transparent graduated scale (G.S.) has lines marked on it 5 mm. apart and lies in contact with the photographic paper (5 mm. = displacement 10 c.mm.). Two lensed flashlamp bulbs (*F.B.*) are placed over each end of the slit and flash for an [illegible]

the paper during recording by means of a hand inserted through a dark-sleeve *in the*

end of the cabinet. A signal indicator bulb is fitted onto one edge of the plate and records onto the photographic paper at one margin (¼ in. wide) which is otherwise clear.

The photographic paper is contained in a magazine (ex-government K.24 Aero Camera, which holds 60 feet). It is driven by an electric motor (ex-aircraft rotary convertor) by means of gearing allowing two speeds of 5 mm. and 10 mm. paper per second. Fine control of speed is provided by a multi-step transformer providing secondary voltage 420 V.–480 V. by 10-V. steps.

The tubes A and B each have a side tube connected to a 3-way tap, into one limb of which is fitted a 1-c.c. tuberculin syringe, graduated to ·01 ml. Each tube is connected to a plethysmograph cup by about 3 feet of 3-mm. bore polythene tubing. An air tank is contained in the cabinet and is connected to a bulb inflator pressure gauge and another 3-way tap, to which the venous occlusion cuffs are connected. All switches and controls are fitted in a small compartment, one wall of which may be folded down and on which the calibrating syringes are fitted.

The instrument is now designed to work off 230-V. A.C. mains, but was originally constructed for 220-V. D.C. supply.

Since it has been shown in Chapter 12 that changes in the height of the pulse wave in the digits are able to give as ready—or even clearer—indication of the presence or absence of vasomotor control, it is probable that a much simpler apparatus could be made for this limited purpose. It would be of no use for estimating the amount of collateral circulation present in cases of peripheral vascular disease, and no visual record would be available for comparison with later examinations.

The simplest form would consist of Perspex or metal toe and finger cups, each bored with one hole to take a '*Luer*'-fitting male adaptor. To this adaptor would be, attached a two-way tap (also of '*Luer*'-bore, as the *Record* size is too small). The side limb of the top would be connected by a short length of plastic tubing to a 1-c.c. tuberculin syringe, and the straight-through limb connected to a piece of transparent plastic tubing of about 1·5-mm. bore and, say, 20 cm. in length. Along part of its length near the end would be attached a short millimetre scale.

In use the patient would first be exposed to the air of a cool room so that maximal vasoconstriction of the digits would be induced when this is possible. Such an apparatus as is described above should be fitted to the index finger or great toe on each side with the rubber grease as is used for digital plethysmography. The transparent tube with its scale should be supported so that it lies horizontally on the bed or a convenient table. By means of the syringe, and with the tap open to all connections, a small amount of alcohol should be drawn up into the transparent tube from its open end so that it forms a column about 2 cm. long. Its position would be adjusted so that the meniscus at one end lies over one end of the scale when the pulsation is at its least. The average of the peaks of the pulsations should be read against the scale and expressed in millimetres. Alternatively, it could be measured by means of the tuberculin syringe.

The procedure would be repeated when the patient has been heated to produce maximal inhibition of vasoconstrictor control. The second reading would be divided by the first and expressed as a pulse heating index. It would be important to see that the cup does not move over the digit during the test and that a standard amount of finger or toe is included in the cup.

AUTOMATIC RECORDING SKIN THERMOMETER

The apparatus will record in rotation up to eleven Eureka copper thermocouples (every half minute or slower, for the same lead). Each lead is indicated by a characteristic symbol, which is printed photographically on bromide paper. The

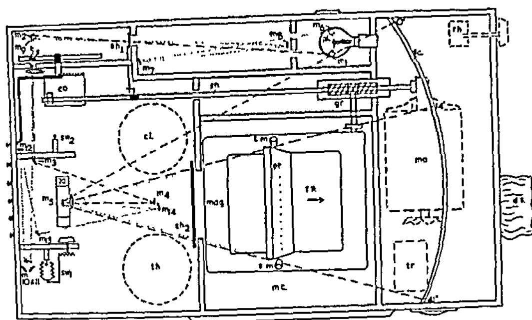
symbols are so spaced that even when the next temperature is the same they only overlap by half their width and may therefore still be easily identified. After developing the record, the like symbols are joined up by coloured inks and appear as a graph, whose co-ordinates, owing to the optical system, are almost rectilinear. Each temperature symbol on the recording may be joined by ink of a different colour. The instrument uses long lengths of 5½-in. wide bromide paper (normal grade) and at the usual sensitivity, 1° C. = 5 mm. over the range 14°–41° C. By means of a switch alternative sensitivities will give 1° = 2 mm. (0 – 50° C.) or 1° = 20 mm. (0 – 6° C.). The actual temperatures are also visibly registered on a scale as they are recorded, so that the progress of the experiment can be followed. On the scale 1° = 7·5 mm. and covers 0°–42° C., so that the null deflection can be read for calibration, though this is outside the range recorded on the bromide paper.

CONSTRUCTION (FIG. 83)

Light beams from the filament of a 12-V. 48-W. projection bulb p^1 (supplied from A.C. mains transformer *tr*) pass downwards through a condensing lens (not shown) onto two plain aluminium-surfaced mirrors m_1 m_6, 1 cm. square. The beam from m_1 is again reflected from m_2 through a Perspex disc which contains a photographically reproduced transparent symbol *s* (appropriate to the lead in circuit) thence through a lens (+4D) onto mirrors m_3, m_4, through the galvanometer lens (+2D) onto its mirror (10 mm. plain) m_5 so that the image is formed on the semi-transparent scale *sc.* at 50 cm. near the top edge of the cabinet. The other light beam from mirror m_6 is reflected from m_7, m_8, m_9 through a similar symbol (there are 3 sets of 11) which lies vertically above the other and is rotated through ½ circle, thence through a separate lens (+1D) on to mirrors m_{10}, m_{11} (to rotate the image so that it appears on the record the same way up as on the scale), onto m_{12}, m_{13} and m_{14} (which lies above m_4) so that the beam strikes the galvanometer mirror at a lesser angle and is therefore reflected at a lower angle than that to the scale. It then passes into the magazine chamber *m.c.* through a slot guarded by a shutter sh_2, which is closed if the top of the cabinet is opened, through a 1½-in. × 5½-in. right-angled prism *pr* onto the recording paper *r.p.* 7 cm. below.

A slow-geared A.C. repulsion motor *mo*, whose speed may be varied by a rheostat *rh*, drives a shaft *sh* which operates the 11 × 3 position commutator *co*, to which the Perspex disc containing the symbols is attached, so that a new lead is brought intermittently into circuit by each rotation of the cam and a new symbol appears in each of the light beams. The commutator should have first-quality non-corrosive contacts, and mercury vacuum switches are to be preferred. Just before this occurs, however, another cam opens a shutter sh_1 in the light beam to the recording paper only, thus exposing it for about half a second when the galvanometer deflection has become steady. The shaft also drives the magazine through 1:100 reduction gear *gr*, so that the paper is spooled towards that end. An electric clock *cl.* makes one minute light time marks *tm* on one edge of the paper, and there is a signal marker *sm* on the other. Provision is made for writing on the record in pencil after inserting the hand through a dark-sleeve *d.s.*

The copper Eureka thermocouple leads are 5 yards long, 28 s.w.g. varnished, and bound together in plaited cotton sleeves, and have a resistance of 20 ohms. The Eureka leads are connected to a common Eureka strip and the copper to individual copper terminals Switch sw_1 selects the requisite Eureka resistance and switch sw_1 will either short-circuit the commutator on to lead *C*, which is provided in order to check registration against a known temperature, or will connect the galvanometer to its critical damping resistance for setting the zero. The constant temperature junction is in ice melting in a vacuum flask *th.* The galvanometer *ga* has resistance 8·8 ohms. sensitivity of 1° A = 15·6 mm at 33 cm. period of one second and is critically damped with about 140 ohms. in circuit (Actually 125 ohms. at usual sensitivity.) The



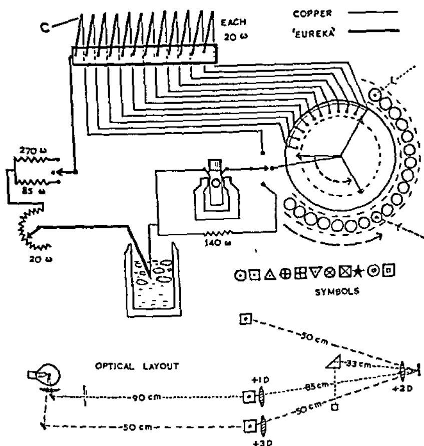


Fig. 83. Plan and diagram of automatic recording skin thermometer.

magazine *mag* is from a K. 24 Aero Camera. The instrument is enclosed in a light-tight cabinet 15 in. × 25 in. × 12½ in. deep constructed from fibre board. It may be wheeled about on a trolley.

This apparatus was first demonstrated in Monro (1951*b*).

ELECTRICAL SKIN RESISTANCE METER

This instrument is a modification of that described by Jasper (1945). Essentially it consists of an 18-V. dry battery and a microammeter, connected through various resistances to two electrodes consisting of a silver-plated ear clip and a brass flat-ended pointer of 1 sq. cm. area. Current will flow in the circuit only when the patient is connected across the electrodes. The ear clip is first moistened with commercial 'electrode jelly' (as used for taking electrocardiograms), so that it will have a low

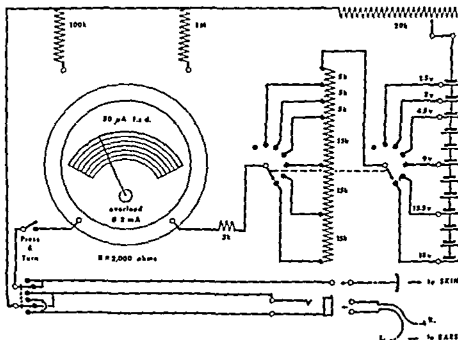


FIG. 84. Circuit diagram of skin resistance meter.

resistance. It is not necessary to prick the skin with a needle to reduce the resistance still further, as in practice, the resistance of the skin of the lobe of the ear without pricking is negligible as compared with the resistance of sympathectomized skin.

Refinements in the design include:

1. A double 6-way + off switch which allows various voltages of 1·5, 3, 4·5, 9, 13·5 and 18 volts to be tapped off the battery and at the same time introduces certain resistances into the circuit, so that even if the electrodes are short-circuited, not more than a maximum of 300 microamperes can pass through the galvanometer.

2. The galvanometer has a full-scale deflection of only 50 microamperes, but is fitted with an overload protection device,* which will protect the moving coil provided that the maximum current does not exceed 300 microamperes. In this way, great sensitivity is obtained over a large range of skin resistances. The scale of the galvanometer is marked in microamperes, but is also fitted with six other scales—each coloured according to the battery voltage in use, and which reads the electrical resistance directly in $\log_{10}$ ohms.

*Makers — Taylor Electrical Instruments Ltd., Slough.

3. An alternative ear clip is fitted, so that the actual resistance of the skin beneath one of them can be calculated, and if necessary their value can be deducted mechanically by reducing the value of the 20,000-ohm variable resistance, so that the galvanometer registers the true resistance of the skin beneath the testing electrode.

4. Eight alternative terminals are provided, so that measurements can be made from separate skin electrodes secured to the skin. This is of use when making measurements of skin resistance at operations for sympathectomy. One is sufficient for the performance of ordinary sweating tests (only one is shown in the circuit diagram).

5. Two standard resistances are incorporated in the circuit for checking the meter and the batteries.

The apparatus is easily carried in the hand. A tube of 'electrode jelly' and the various wires, ear clips, etc., are contained in a compartment in the lid, which is detachable. The circuit diagram (Fig. 84) and the calibration chart are also fitted to the lid of this compartment. It is impossible to close the lid with the ear electrode jack-plug in position and therefore the batteries cannot be discharged accidentally.

In practice the voltage is adjusted to give a full-scale deflection of the microammeter when the testing electrode is placed on normal skin, but of only a few microamperes when it is in contact with sympathectomized skin. Current will flow only when the skin electrode is in contact with the skin: the apparatus is therefore economical and the batteries should last a year. A normal subject is able to detect a current of 30 [illegible] here a current of [illegible]

[illegible] the provision of alternating current at the same voltages instead of direct current. This alternating current is obtained from the mains by a small built-in transformer. A bridge rectifier supplies only direct current to the meter.

A suggestion for future models would be to increase the range still further by providing voltages up to 45 volts. More than one ear electrode is not essential.

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